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PROCEEDINGS

SIXTH MEETING, FIRST HALF, 64TH SESSION

In the Chair: THE PRESIDENT, COLONEL THE MASTER OF SEMPILL

WEIGHT OF AIRCRAFT

BY

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The PRESIDENT: Major Barlow has been one of the leading Technical Officers in the R.N.A.S. and, later, in the R.A.F. He was responsible for putting into operation the very excellent system now used at Martlesham Heath when testing the performance of Service and civil aircraft.

The system had been a great success, and had been copied in a large measure by foreign establishments of a similar character.

He was now Chief Engineer of the Fairey Aviation Co.

1. INTRODUCTION

Major T. M. BARLOW: All historical records of aviation from the earliest attempts at flight to our present-day Schneider Trophy and other record flights, show that in common with those nineteenth century experimenters our modern engine and aircraft designers are in one continuous struggle with the physical laws of weight. It is true that the early pioneers were faced with the problem of flying as such to the extent of carrying one man by a heavier than air machine a few hundred yards, but once this was achieved development quickly enlarged the problem, and weight, with its relationship to power, lifting surface, safety factors, performance, range, and later—with the coming of civil transport—financial weight in the form of pay load, have become the all important item with the aeronautical engineer and constructor.

A remark, originally made by a well-known British constructor that he would "spend a pound to save a pound anytime," is actually a sound economic truth. This saying applied to military aircraft; the meaning he wished to convey being that 100lbs. saved on a total weight of a particular type would produce orders owing to increased performance of the lighter aeroplane, apart from

reduction in cost of materials and building a lighter structure, to an extent of £100 sterling profit to him. In another way it has been adapted to civil aircraft by the Assistant Secretary of the Aeronautical Branch of the U.S.A. Navy, in discussing transport work, that a 10 per cent. increase in structural weight on civil aircraft would only be justified if accompanied by a decrease in total cost of the aircraft of 20 per cent.

In fact world competition for both military and commercial aircraft has compelled engine and aircraft engineers and metallurgists to study the weight problem in minute detail and all its phases and effects so that maximum efficiency in the comprehensive sense of the term may be obtained. I propose, therefore, in this paper to summarise various characteristics and influences affecting the weight of aircraft with a review of possible development with increased size. I have not attempted to deal fully with the effect of using different materials in the construction of aircraft as this is a design problem and in any case too lengthy a subject to be discussed in a lecture of this nature.

2. Performance and Weight

One of the first problems which an aircraft designer must cope with in any particular aircraft projected to comply with a definite specification, is the provision of a correct balance between weight and resistance for maximum efficiency. For example, the following alternatives may be under consideration, biplane or monoplane with their structural differences; installation of air-cooled engines or water-cooled engines; type of fuselage involving length and section; undercarriage with straight axle or independent wheel axle structure; or, for example, a boat hull with different methods of construction and tail unit designs. Apart from practical or operational parts bearing on the design, all alternatives of this nature are reduced to the compromise which has to be effected between weight and head resistance—or performance and weight.

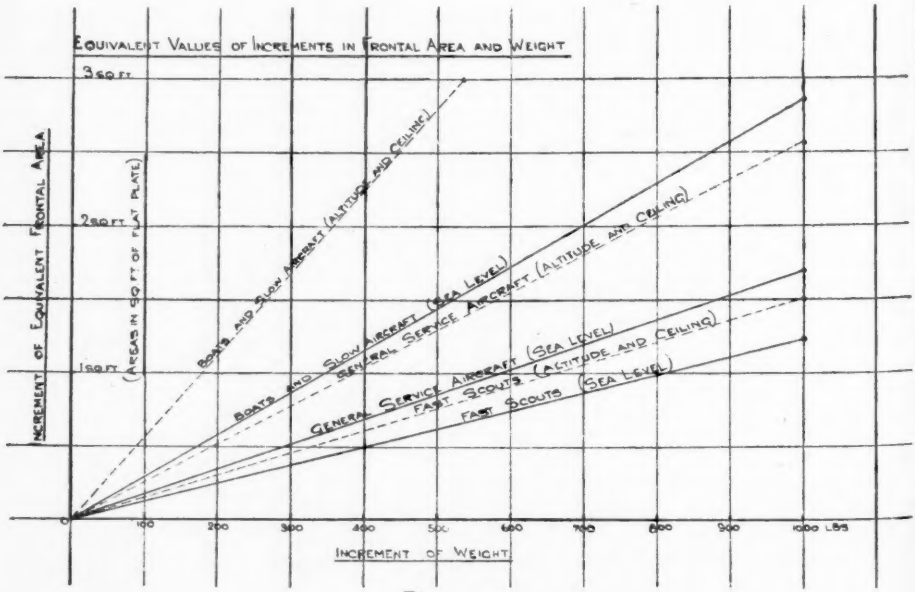

FIG. 1.

It is difficult to treat this subject in an entirely general way; on the other hand an individual case is not helpful to a solution of the problem and may be misleading. I have therefore divided aircraft into three classes for investigation.

(*a*) Fast types as single seater fighters and high speed day bombers.

(*b*) Medium speed types as general purpose military aircraft.

(*c*) Slow (relatively) speed types—large flying boats, heavy bombers and commercial aircraft.

The corresponding speeds being of the order of 200 m.p.h., 150 m.p.h. and 100 m.p.h.

The latter speed may be thought low but it should be treated relatively to the speeds of the other types. Other assumptions made are a loading variation of (*a*) 14 lbs./sq. ft., (*b*) 12 lbs./sq. ft., (*c*) 10 lbs./sq. ft. Further, by virtue of the Specification, range, landing speed, structure strength, are assumed to be constant. Small differences in these will not affect the final comparative result, which has been plotted in the form shown in Chart 1, to an appreciable extent.

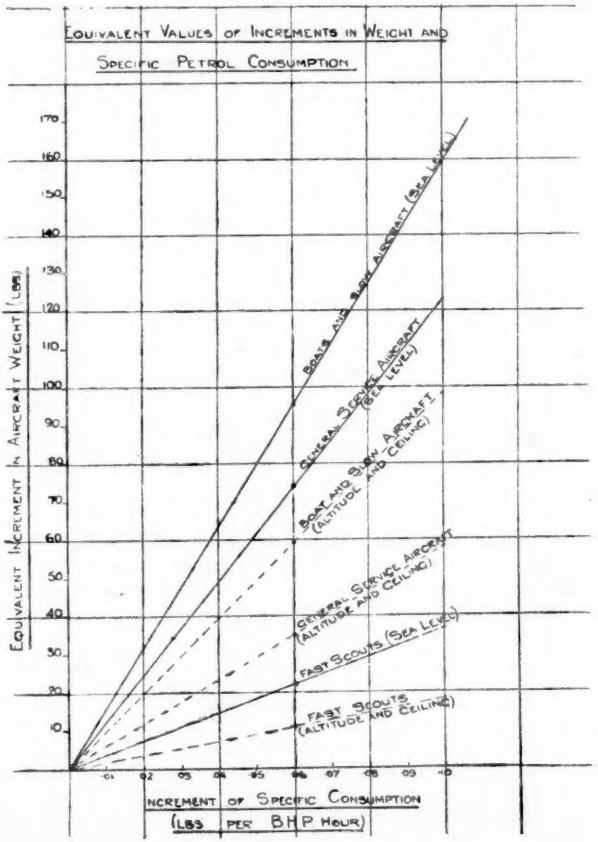

FIG. 2.

You will observe from the Chart the marked difference there is on the comparative effect of weight and head resistance at altitude compared with sea level. For example in the general service aircraft in comparing performance at altitude (15,000ft.) 1 sq. ft. of equivalent flat plate head resistance is equivalent to a 400lb. weight difference whilst at sea level this is increased to 600lb. We have a practical example in the case of the air-cooled and water-cooled types built to the same specification. The extra head resistance of the air-cooled power plant cannot outweigh at the lower altitudes the weight differences of the power plants; at extreme altitudes however they become equal, or the scales may even turn the other way. For the high speed types the differences for sea level and altitude are smaller but the weight increments are naturally larger.

Without entering into the air-cooled versus water-cooled controversy it is extremely interesting to apply this data to an actual case with the additional correction for differences in consumption. The air-cooled engine consumption figure is definitely higher than that of the water-cooled engine and therefore this weight difference must also be accounted for. Chart 2 has been prepared for types as on the previous chart with increments of specific consumption—lbs. per b.h.p. hour plotted against aircraft equivalent weight increment. Consider the weight difference of two modern British water-cooled and air-cooled engines which amounts to 450lb., water, etc., being allowed for, the equivalent frontal areas correct as follows:—

	Original Weight Increment.	Correction for Consumption.	Corrected Weight Increment.	Equivalent Frontal Area Sq. ft.
(*a*) *Sea level.*				
Slow aircraft	450	96	354	1.02
General service	450	74	376	.64
Fighters	450	22	428	.53
(*b*) *Altitude.*				
Slow aircraft	450	59	391	2.18
General service	450	35	415	1.06
Fighters	450	11	439	.66

Now there is a definite physical fact which places the air-cooled resistance figure of engines of the power under consideration at approximately 1½ sq. ft. higher than the water-cooled power unit; one can therefore judge this effect compared with the weight differences as expressed in the above Table.

3. Factors and Weight

The question of safety factors to be adopted for any specific type of aircraft is at the moment under discussion by aeronautical engineers and international and other bodies concerned with official control of flying. The I.C.A.N. have issued regulations basing factors on the all-up weight of the aircraft only with no reference to speed, range, performance or power loading. Military aircraft factors are at present in the majority of countries based on type and duties of the particular aircraft. Chart No. 3 indicates in general the factors called for according to Standard British Practice. The results are rather illuminating and show definite inconsistency in making "weight" the deciding influence on load factors. You will observe that in the case of general service type of military aircraft, which form by far the largest percentage of every country's aerial strength, that the factors are approximately one unit factor down below those required for a civil machine—acrobatic category. There is a similar anomaly in the slower aircraft. Whatever decision is finally arrived at on this factor question it does not influence an analysis of structure weight being made

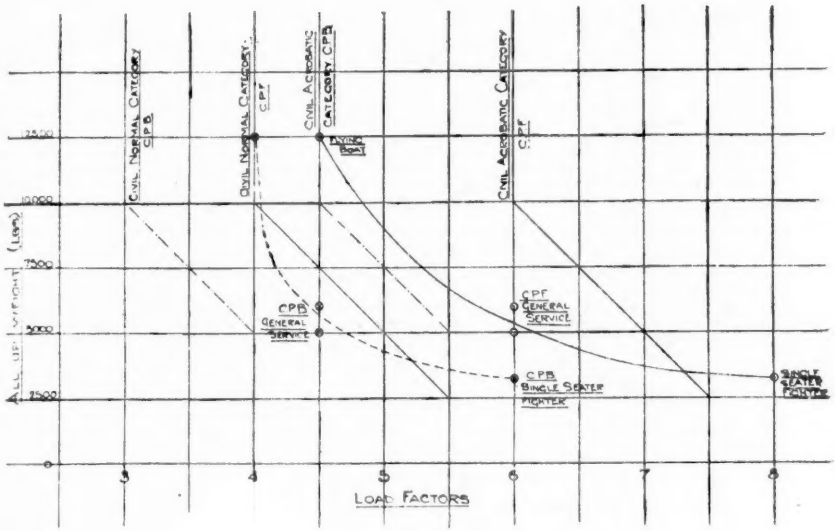

FIG. 3.

with respect to small changes of factor such as might occur in a re-drafting of Chart 3.

For this purpose I propose to consider an individual type—an aircraft of the size of a Standard two-seater single bay design of which percentage structure weights are well known. Any change of structure weight with load factor is considered to have no aerodynamic change. Various parts will be affected differently and these may be classified as follows:—

(*a*) Independent of factor—items such as cowling, fairing, fabric, controls, etc.
(*b*) Varying directly with factor—wires, lugs, fittings, short struts.
(*c*) Structure members—long struts.
(*d*) Structure members—beams without end loads.
(*e*) Structure members—beams with end loads.

The first two require no further explanation.

Consider (*c*) (*d*) and (*e*). Taking the ratio of load factors to be "n," it is found, presuming geometrical similarity, that for

Long struts	W varies as $n^{1/2}$
Beams with end loads	W varies as $n^{2/3}$
Beams without end loads	W varies as $n^{2/3}$

The structure weight of the typical aircraft may be summarised thus:

Designed to the following factors:—

C.P.F.	7	
C.P.B.	5	
Inverted flight	3·5	
N.D.	1·5	
Torsion	2	$Ky = 0.5$ at 1.4 × stalling speed
Landing	4·5	

All-up weight taken as 100%

Structural items :

Wings	15.5%
Fuselage	10.6%
Tail Unit	1.7%
Chassis	3.2%
Structure weight	31.00%

Items as detailed above :

	Wings.	Fuselage.	Tail Unit.	Chassis.
(*a*)	4.2	4.30	0.60	0.25
(*b*)	2.55	2.88	0.29	1.48
(*c*)	1.55	2.90	0.43	1.07
(*d*)	3.30	0.52	0.38	0.40
(*e*)	3.90	—	—	—
	15.50%	10.60%	1.70%	3.20%

The following table is indicative of changing the C.P.F. factor from 5 to 9 for this particular case.

Weights in percentages :

Structure Involved.	Wings 50% Front Truss.	Fuselage 1/3rd effected.	Total.	Factor 5.	Factor 9.
(*a*) Independent	2.1	1.43	3.53	3.53	3.53
(*b*) Varying directly ...	1.275	0.96	2.235	1.60	2.88
(*c*) Struts	1.275	0.966	2.241	1.89	2.545
(*d*) Beams	1.65	0.173	3.773	3.025	4.460
(*e*) Beams	1.95	0.173	3.773	3.025	4.460
Totals ...	7.75	3.529	11.779	10.045	13.415

Chart No. 4 gives these results in curve form, which interpolated roughly shows that a change of one unit in load factor means approximately 1 per cent. change in the structure weight or in terms of a type weighing 5,000 lbs. change of factor from 6 to 7 C.P.F. can be obtained at expense of another 50 lbs. Similarly, a variation is obtained for C.P.B. factor. I must emphasise that this theoretical analysis must be associated with similarity of geometry.

Effect of variation in the remaining factor (Terminal Dive), usually scheduled in Specifications, on weight may be analysed in the same way. Prediction is difficult as the majority of members are affected by C.P.B., torsional, and N.D. loads, and variation of any one case may change the order of precedence.

The method of obtaining torsional loads due to side loads on the fin and rudder is empirical and the load factor of 2 contained in the assumption remains constant for all classes of aircraft.

Thus the factors of non-torsional cases cannot be reduced indefinitely and still produce a corresponding reduction of structure weight, as the constant torsional loads for the given geometry of rear end, fin and rudder, will impose a limit.

However, the following members may be presumed to be affected by N.D. conditions only, for small variations of load factor.

Tail plane.
Rear fuselage bottom longerons.
Half the side wires—rear fuselage.
Some centre section members.
Bottom front spar bay.
Some main plane drag wires and struts.

Carrying out an analysis by the same method, Chart No. 5 may be plotted which indicates a percentage weight increase of $1\frac{1}{4}$ per cent. for a $\frac{1}{2}$ N.D. Factor variation.

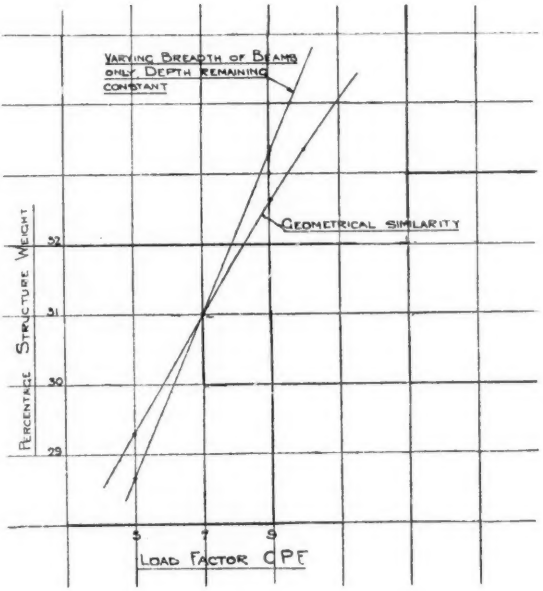

FIG. 4.

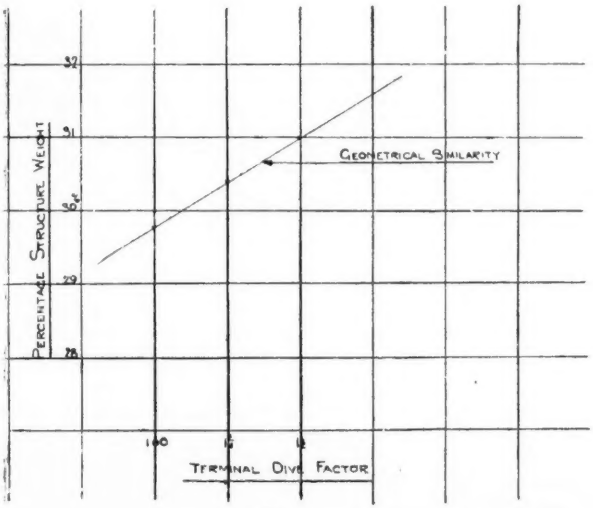

FIG. 5.

Summing up to change a 5,000 lbs. aircraft with factors C.F.P.5 and C.P.B.4 N.D.$1\frac{1}{4}$ to C.P.F.7 and C.P.B.5 with N.D.$1\frac{1}{2}$ involves a weight increase of the order of 180 lbs. In actual practice it must be realised that often factor change involves excess weight, as for instance standard plate gauges, standard tube diameters and gauges, bolts and wires, etc., naturally cannot always fit in with the increment of load to keep the resultant stress within the prescribed limits.

4. Aircraft Materials and Weight

Ten years ago practically all aircraft structures consisted of wood (either spruce, ash or ply) and mild steel in the form of tube, bar or sheet. Choice of materials was necessarily limited during the war period and weight-saving depended therefore on the skill and the ingenuity of the designer rather than on a judicious use of larger varie[illegible] materials and metals. The metallurgist, however, has made rapid strides, and about the end of the war an entirely new field of materials was opened up by the production of aluminium and aluminium alloys in sheet bar, and cast form together with an extensive range of steels available not only in the usual forms but in the finer gauges—high tensile steel strip—which allowed the aircraft designer to make full use of this particular material.

The limitations of wood as a material of construction are well known and have been dealt with *in extenso* by the many exponents of entirely all-metal aircraft, but leaving out of the question the possibility of shortage of suitable wood in a war crisis there is no doubt that even to-day there are units which are more profitably manufactured in wood than metal on the score of weight. I was reading the other day an explanation by a well-known international engineer and designer (Fokker) giving the reasons why he still retained wood construction for his monoplane wings as opposed to a steel or light alloy construction. It could be summed up in one word—fatigue. We as aeronautical engineers are not alone in our lack of knowledge of this problem, but unfortunately we cannot, as other engineers, play for safety by adding excess weight. One must therefore review all our new materials with their claim to lightness in association with their fatigue limits. The ratio of the weights of the three principal materials of construction are:—

Spruce	0.48
Aluminium alloy	2.75
Steel	7.85

which, of course, must be associated with their mechanical properties. Taking these into account the values of wood as regards elastic limit and fatigue predominate. Fatigue in properly seasoned wood is unknown. One notes, however, that the aluminium alloy is inferior in this respect, and that according to recent tests carried out by the Materials Division of the Air Corps, United States, the specific fatigue limits of aluminium alloy, ordinary high-grade steel and heat-treated chome molybdenum steel are roughly in the ratio of 4.5, 5, to 11. I emphasise this to indicate that the lightest material is not always the most suitable one for parts subjected to alternating loads and vibration such as would be experienced in certain parts of a wing structure or engine mounting.

For a direct comparison it is interesting to note the differences in the design of a spar constructed in four different materials now in standard use, *i.e.*, spruce, tubular section steel, steel strip and duralumin.

The equivalent sections are illustrated on Chart No. 6. For spruce a typical box section has been chosen, for the steel tubular section a type known as the "Double 8," for the high tensile steel strip a typical drawn flange with straight web, and for the duralumin a section on lines of Breguet.

The results are extremely interesting and are tabulated:—

Type of Spar.	Allowable Stress.	Weight Ratio.	Stiffness Ratio.
Spruce.	5500 lbs./sq. in.	1.00	1.00
Tubular.	40 tons/sq. in. (T.5).	0.75 wood/steel.	0.76 wood/steel.
Strip.	65 tons/sq. in. (S.40).	1.25 wood/steel.	1.24 wood/steel.
Duralumin.	17 tons/sq. in.	1.08 wood/dural.	0.915 wood/dural.

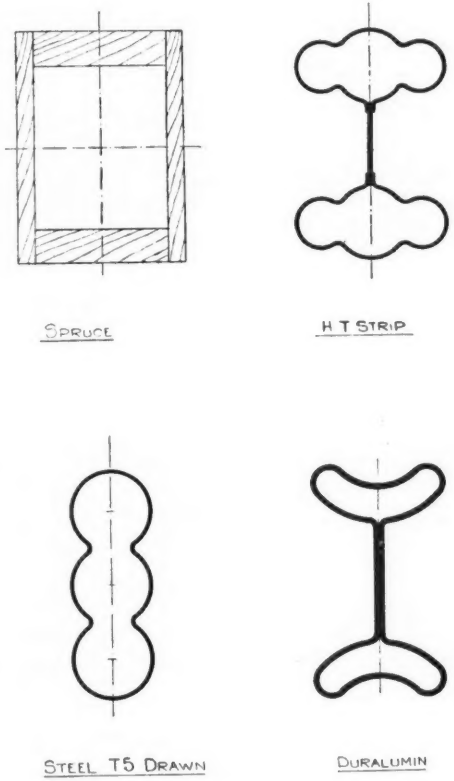

FIG. 6.

Fuel and Oil Tanks, Pipe Lines

Of the independent units on aircraft which have definitely proved to be an appreciable saving in weight by change of materials, tanks are an outstanding example. Weight has been reduced by changing from the original brass and copper tanks to tinned steel, and then to the now almost standard material, duralumin and aluminium, in approximately direct proportion to the specific weights of these materials. The differences may be judged from the following table of a 54-gallon petrol tank built to the same overall dimensions. Strictly interchanegable in mounting and passing the same pressure tests for the three materials:—

Material.	SWG.	Weight.	Joint.	Finish.
Duralumin (nickel coated to facilitate soldering).	20	26	Soldered and riveted.	Tung. oil varnish.
Tinned steel.	26	43	Ditto	Grey paint.
Aluminium	18	29·5	Welded and riveted.	Anodic.

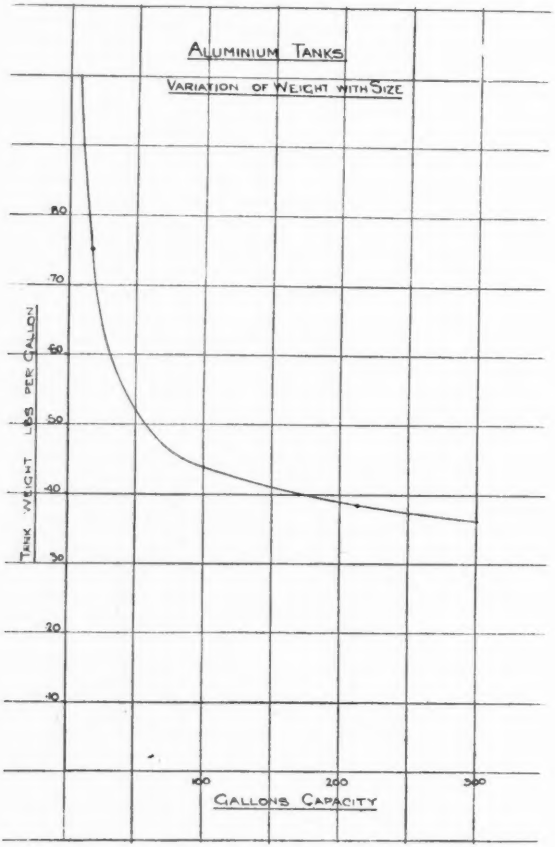

FIG. 7.

A 30 per cent. reduction is effected between the steel and aluminium.

The effect of size of tank on weight of tank per gallon capacity is rather instructive. Chart No. 7 has been drawn up from weights of a series of tanks in aluminium. It should be noted that the smaller tanks are naturally more complicated in design, and this factor accounts for the rapid increase in weight per gallon with decrease of capacity below the 100-gallon mark.

Associated with tanks are pipe lines. Here again material has effected a weight reduction, but with not such satisfaction owing to the fatigue stress which such parts have to withstand when linked up with any power unit which has a

period inherent in the design; although of course even a smooth running engine when out of tune has its bad times with vibration. The use of metal couplings does not help much; in fact, a new synthetic material is wanted for joints with the elasticity of rubber, but as durable and as proof against all types of fuel as metal.

Comparison of ½in. bore pipe lines have been made, gauges being adjusted for practical consideration, the weight per foot run showing on this score a decided advantage to duralumin.

Material.	Gauge.	Weight per foot (lbs).
Aluminium	20	0.0625
Duralumin	22	0.039
Copper	20	0.14
Petroflex	—	0.31
Stainless H.T. Steel ...	24	0.114

Choice of the most suitable for particular parts of the circuit must not be governed entirely by weight, but resistance to fatigue and reliability in service, and here duralumin fails to reach the standard of copper or aluminium.

Wheels

Before leaving this section I want to refer to an item of structure weight—landing wheels. They form anything from 5 per cent. to 7 per cent. of the structure weight and therefore have a definite place in weight analysis apart from their aerodynamic effect.

Chart No. 8 shows that round about a wheel load of 5,000 lbs. weight of the standard type of wire spoke steel rim wheels is approximately 2 per cent. of the load, a figure tending to increase in higher sizes and decrease in the lower due to differences in type construction. Also alongside this curve has been plotted the projected frontal area of the various wheels. Here the area in proportion increases slightly with the total load.

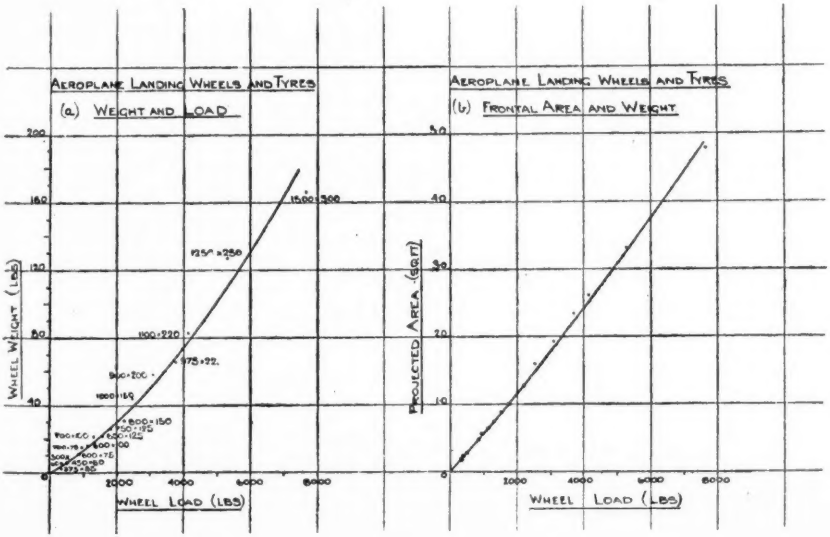
AEROPLANE LANDING WHEELS AND TYRES
(a) WEIGHT AND LOAD
WHEEL WEIGHT (LBS)
WHEEL LOAD (LBS)
AEROPLANE LANDING WHEELS AND TYRES
(b) FRONTAL AREA AND WEIGHT
PROJECTED AREA (SQ FT)
WHEEL LOAD (LBS)

FIG. 8.

5. Power Unit and Weight

(a) Engines

The weight per h.p. index for all types of engines has undergone definite decreases during the last ten years due both to improvements in basic design such as working at higher mean effective pressure, running at high revolutions, air-cooled cylinder design, and to metallurgical progress which has permitted the use of light alloys and super grade steels in highly-stressed parts. I have prepared a chart, No. 9, which is particularly instructive as showing this weight reduction up to the present time with an indication of what we may expect if

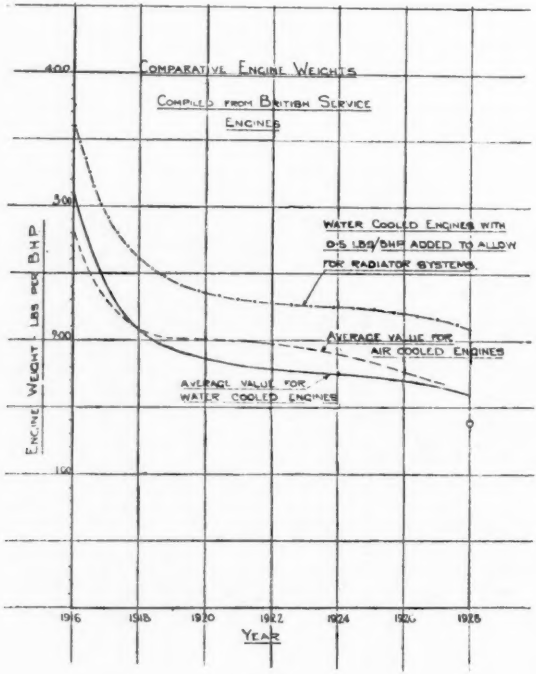

Fig. 9.

the experimental work of our engine constructors is fulfilled. It will be observed that both of the main types, air-cooled and water-cooled, have improved approximately to the same degree with a marked step down in weight per h.p. for the new air-cooled "V" engines which are now experimental types in U.S.A., France, Italy and England. In connection with the figure chosen for the average weight of water-cooling system "radiator and water" one must not overlook the possibilities of evaporative or steam-cooling as it is commonly called. Experiments have already shown that practically no change in design of water-cooled engine is required—certainly none involving an increased weight to allow running under steam-cooling conditions. A big percentage reduction, however, is possible both in actual radiators and volume of water, a conservative estimate being a reduction of 50 per cent., bringing the average weight increase for cooling systems of the water-cooled engines down to 0.25 lbs./h.p. (from 0.50 lbs./h.p.).

Progress in further reduction of this weight per h.p. figure can be made by taking more advantage of that part of the engine which, figuratively speaking, weighs nothing—I mean " revs." I foresee the future types running normally at well over the 3,000 mark—our Schneider trophy engines are beyond this now—with suitable gearing for obtaining best possible airscrew efficiency.

Supercharging will increase weight for a time, but increased speed will gradually reduce specific weight again. Starting gear weights are likely to remain constant. Ignition will be lighter if development on the lines of the double armature magneto are proceeded with. Increase in compression ratios and mean cylinder pressures tend to more efficient use of weight, but it must be noted that a mean increase means a maximum increase with consequent difficulty in design stresses.

Before discussing the effect of size on engine weight I must refer back to the material question. Our war-time engines were somewhat restricted in their choice apart from the fact that the metallurgist had not reached the present high standard in super steels and light alloys. It is interesting to note that one cylinder block unit of well-known modern engine contains fifteen different materials:—Duralumin, magnesium, aluminium, bronze, two specifications of nickel-chromium steel, two specifications of carbon steel, cast iron, brass, copper, cold-rolled steel, drill steel, chrome-vanadium steel and silchrome steel for valves.

The reduction in engine weight by the use of the higher grade steels, however, is small to that gained by the use of the higher grade light alloys in parts such as crankcases, die forged duralumin, which are approximately 10 to 12 per cent. lighter than the usual crankcase alloys and something like twice as strong. A still further reduction will be possible as the use, in production, is made of magnesium alloys. I realise that the corrosion problem is not fully solved, but there is evidence that slight variations in the aluminium content of the alloy is an improvement in resistance to this defect, and one must remember that " oil " is always present, affording one of the best protections known. Magnesium alloys are 47.5 per cent. lighter than the normal aluminium alloys, and weight for strength has a ratio of 1.4 to 1 in favour of the former. As with the aircraft structure, so with the engine, we aircraft engineers look to the metallurgist for still more help in this weight problem.

The next weight ratio to be criticised is perhaps not strictly an engine part, but is definitely a power unit index, *i.e.*, fuel consumption in lbs./h.p. With all due respect to our carburettor designers, progress from the end of the war until last year afforded little which reduced this figure. In some way as regards aircraft engines this may be due to official type test conditions, which usually quote a rather generous minimum consumption figure as a requirement at normal rating with no restriction as to consumption with the engine in the throttled condition, which after all in civil air operation is the flying condition and to almost the same degree in military work.

From Chart No. 10 can be judged the appreciable weight advantage which is possible by attention to this part of the power unit, which, without any increase in weight of itself, can by design affect size, weight and range of a complete aircraft.

As an example of its effect in fuel-saving alone, apart from tank structure, etc., a twin-engine type commercial aircraft (nominal h.p. of each engine 500) of a cruising speed of 100 m.p.h. would be capable of carrying approximately 400 lbs. extra *paying* load by working on the lower curve of the chart at a range of 500 miles. Fuel taken as 0.74 sp.g.

The effect of size on engine weight—by that I mean variation of lbs. per h.p. with the total h.p. of the engine—rather leads one to the air-cooled versus water-cooled engine controversy and also confirms that both types have their position in aircraft development.

The curves on Chart No. 11 show quite clearly the advantage of the air-cooled on the score of weight—not aerodynamically—up to between 455 and 500 h.p. At this point weights are approximately equal, but for the higher figures up to 1,000 h.p. and over water-cooled engines only are available. This chart, however, does not disclose the true comparison as no account is taken of any resistance of the power unit or fuel economy.

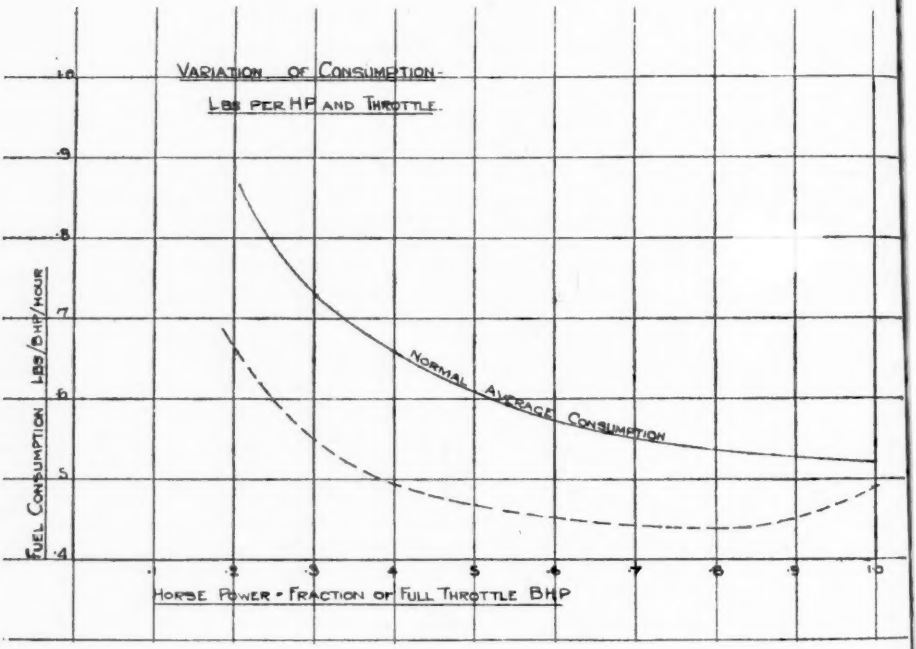

FIG. 10.

(b) *Airscrews*

There are many weight analyses made during the preliminary design stages of aircraft which I think you will find in the majority of cases take an airscrew weight very approximately without thought for any saving which may be effected. Airscrews do form an appreciable weight percentage of a power unit varying from 8 to 12 per cent. of the engine weight. Airscrew weight is important for aerodynamic reasons; as a unit it is the most forward part in a standard single-engine tractor design and there influences the centre of gravity position correspondingly. In other designs its influence is not so effective but always appreciable.

Now design does not help us in any form of weight reduction and we are forced to turn entirely to materials of construction. Wood, until the last few years, was the only material adopted, but flying operations have so changed in that weather conditions, temperatures and climates which formerly were considered impossible are now normal, that apart from aerodynamic efficiency we have been forced to the less vulnerable steel or light alloy with consequent increase in weight. The weight ratio of airscrews built and designed for the

same engine and aircraft in the three materials is as follows (all complete with boss) :—

Mahogany, 84 lbs.
Hollow steel blades, 108.5 lbs.
Duralumin, 106 lbs.

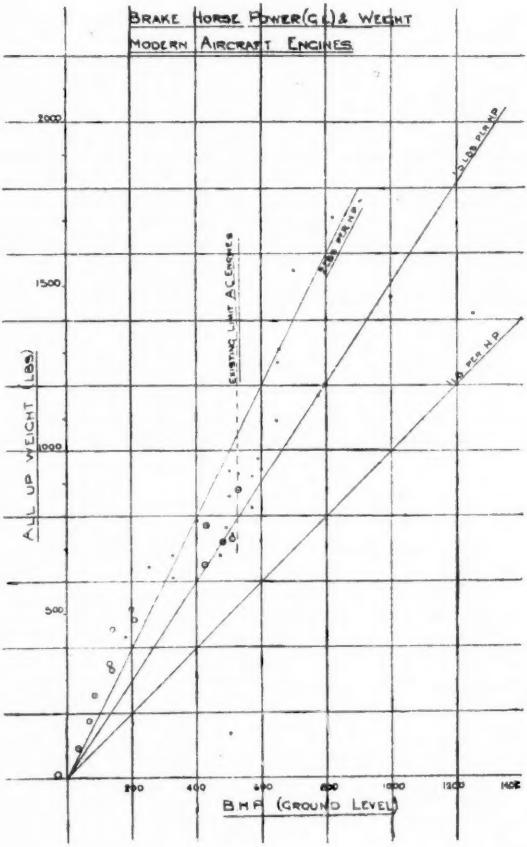

FIG. 11

For practical considerations and durability we cannot return to wood, and I therefore do not see much hope for weight reduction in this direction until airscrews are developed using some of the new lighter magnesium alloys. Here the corrosion problem is acute, especially for sea aircraft. All airscrews are naturally subjected to erosion, especially near the tip and along the leading edge. This may be due to running upon the ground in the case of land aircraft, as even on the best finished tarmac there is always a fine dust sucked up capable of wearing the surface in time. In all types there is erosion from hail and rain; in seaplanes, spray. One realises, therefore, that the usual protective coating of light alloys is not sufficient for the still lighter alloys such as magnesium-copper or electron, as any erosion forms the easiest path possible for corrosion.

There is a further disquieting feature arising with airscrew weights. Engine powers and revolutions per minute are arising, involving gearing, thus necessitating larger diameters and more blade area to take full advantage of efficiency. Chart No. 12 has been prepared which shows the variation of weight with

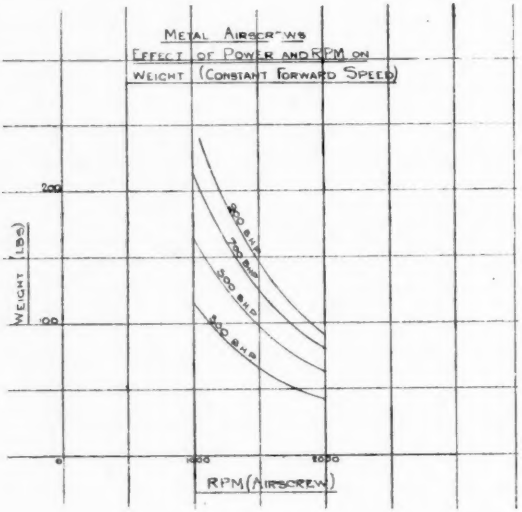

FIG. 12.

airscrew r.p.m. for the same forward speed and b.h.p. The chart is intended only as a very approximate indication of the effects of this recent engine development. The weights are not necessarily as high as shown on chart, which implies in each case the diameter most appropriate for the gears. You will observe this becomes very large at low r.p.m.

It will also be noticed that the weight of an airscrew required to absorb a constant power varies inversely as the r.p.m. for the same forward speed. Consequently for a geared engine additional weight must be allowed for in addition to the gear weight; whether the increase in efficiency warrants such an expenditure of weight is a matter for consideration for each particular design as in certain cases a larger propeller might mean larger undercarriage for land or sea aircraft, which means still further weight and head resistance—the vicious weight circle. Each design therefore has a particular balance of these variations.

6. RANGE AND WEIGHT

I have mentioned under the section of "Power Unit Weights" the importance of engine consumption on total fuel weight on range. This can easily be elaborated and analysed for any particular specification. Range depends, in addition to engine consumption, on the ratio of aircraft laden to aircraft light, and the overall L/D ratio. To judge weight effect as many variables as possible will be eliminated.

The total weight may be divided into four parts:—

Structure weight	W_g
Power plant weight	W_p
Useful load	W_v
Consumable load (fuel, oil, etc.)	W_f

If similarity of design is assumed the structure may be kept at a fixed proportion of the all-up weight. The power plant weight (except tanks) remains constant; the useful load can remain constant. Then the weight ratio may be expressed as

$$(W_g + W_p + W_v + W_f)/(W_g + W_p + W_v)$$

The extent by which the weight ratio may be increased depends on the run to take off which follows from the wing loading, the power loading, and the overall L/D. For a given engine the power loading is known, and if the variation of overall L/D with weight is fixed, then for a given run-off the wing loading may be determined. The variation of overall L/D with weight depends on (*a*) wing drag, (*b*) body and parasite drag. The wing drag coefficient can be made constant by arranging for the aspect ratio to remain constant with change of area. The body drag will vary with all-up weight, but not necessarily directly. The type of engine and the number of crew will indicate the size of fuselage at a normal all-up weight, and then as the load is increased a stronger and larger chassis will be required and the increasing main plane chord will necessitate larger tail surfaces and longer fuselage, resulting in an increase of body resistance.

The variation of weight with range has been investigated on these lines for a particular case using a power unit of a nominal 575 h.p. water-cooled engine.

Useful load	1,200 lbs.
Power plant	1,800 lbs.
Structure weight ...	30 per cent.
Run to take off	500 yards.
Head resistance	$10 + .0005\ W$.
Aspect ratio	Constant.

The results have been plotted on Chart No. 13, taking an all-up weight of 6,500 lbs. for example, the range will vary for a consumption of 0.6 lbs./b.h.p./hour to 0.5 lbs./b.h.p./hour from 780 miles to 930 miles. Similar charts may be constructed for other types.

The range/weight ratio may also be reviewed with respect to limit ranges.

An attempt has been made to provide a solution of the problem in a very academic fashion by considering an aircraft of unattainable efficiency.

This would consist of a flying wing with so little parasite resistance that its influence may be neglected, and to simplify the problem slip resistance has been neglected.

With the normal method of take off (acceleration from airscrew thrust only) long range inevitably means an association of wing and power loading which just enables a heavily-laden machine to stagger off, and this limit is being approached at $W/s = 20$ and $W/p = 30$.

The useful load W_v can be used to transport a large load for a small distance, or a small load for a great distance, by replacing load W_v with fuel W_f.

In the case of a special long range aircraft the load has to be reduced to a minimum so that the maximum amount of fuel may be carried; however, the crew and equipment will weigh at least 500 lbs. The wing has been assumed to have suitable aerofoil characteristics (minimum profile drag in the region of 0.40 lift coefficient) and an aspect ratio of 7.5. It will be obvious that structural weight is superlatively important when considering long range, and reduction in this direction depends particularly upon load factors which must also be reduced to the minimum.

In the particular case under consideration, namely, a wing without parasite resistance, the weight of structure suitable for cantilever construction is unlikely to be less than 25 per cent. of the total weight.

The following constants have been taken for the calculations:—

Power plant weight	... ...	$2\frac{1}{2}$ lbs./b.h.p. installed.
Fuel at	... ...	7.28 lbs./gallon.
Tankage	... ...	0.50 lbs./gallon.

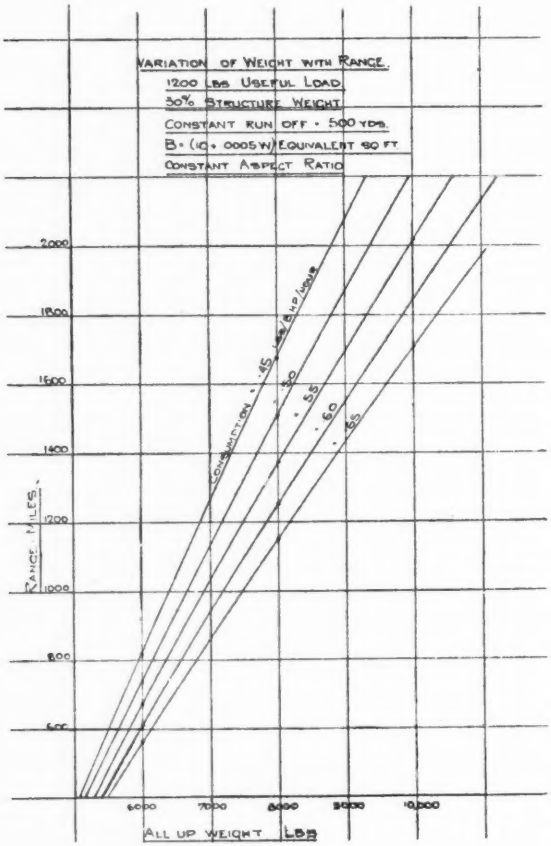

FIG. 13.

In order to demonstrate the value of aerodynamic cleanness, curves have also been added for head resistance represented by $B/W = .001$ and .002, where B is the resistance in equivalent sq. ft. (one equivalent sq. ft. has a drag coefficient = 0.65).

With these limitations the only way in which range may be increased is to increase the total weight until the effect of useful load (crew and equipment constant = 500 lbs.) is completely swamped by the total weight.

Results have been plotted on Chart 14 for several consumptions, and it can be seen that an all-up weight of 50,000 lbs. represents the limit of range, and furthermore that a non-stop flight of 10,000 miles is outside the range of possibility with present-day engine consumptions.

7. Influence of Size on Weight

We have recently heard before this Society lectures by two eminent Continental aeronautical engineers (Dornier and Rohrbach) which dealt with the design and construction of large flying boats. An analysis of the very full data of Dornier's paper especially confirms my opinion that there are no reasons, theoretical or practical, why this type of aircraft should not be developed immediately to a size and weight which, as far as I am aware, has to date only appeared in those wonderful artists' dreams of air transport ten or twenty years hence.

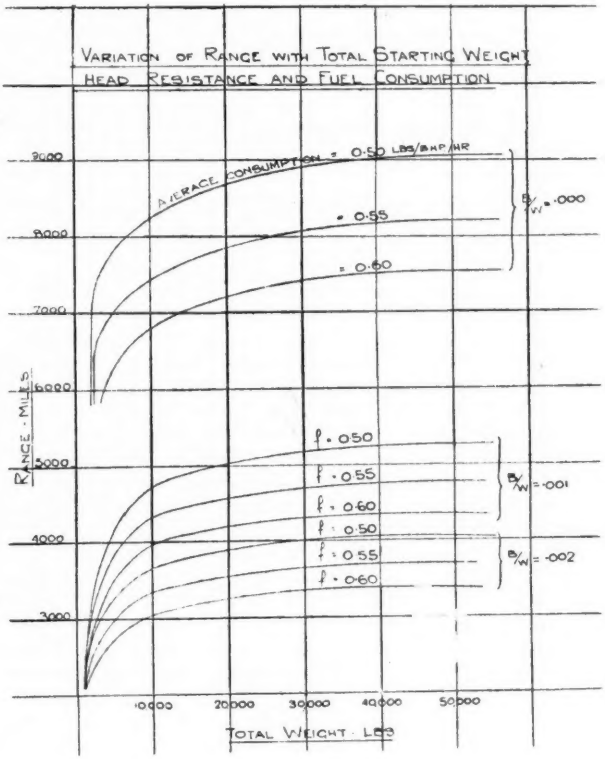

FIG. 14.

There are definite limits to the size and weight of aeroplanes of the land type as distinct from flying boats for both military and civil duties. Firstly consider the military side. Aeroplanes of super size would be built to fulfil certain special conditions, either for (1) very heavy armament in the way of guns and bombs, or (2) extreme range, meaning a heavy fuel load, or (3) transport of men or munitions, all such loads being alternative in divisions or as a whole. The aerodynamic practical limits on power and wing loading at the moment are approximately 18-20 lbs. per h.p., 12-16 lbs./sq. ft., and I see no reason for any radical alterations in this respect with known forms of prime

movers. Freedom of munition construction and freedom of use or action when constructed form the key to all modern successful war operations, and it is interesting to note how restrictions under these conditions affect super large aeroplanes. Freedom of construction is limited to a size the main units of which may be transported by ordinary means over rail or road. Special arrangements which require road or rail to be clear of all other traffic of course cannot be considered as a war proposition. The alternative is construction, in addition to erection, at definite aerodromes suitable for the type of aircraft, an impossible "proviso" under war conditions when practically all engineering shops must turn over to production of war material. There is, of course, the additional point that all aerodromes will be the principal bases to be attacked by air. It is possible to transport by road (the rail limits are lower) units up to approximately 60 feet long by 15 feet high and 12 to 13 feet broad without much difficulty. On this basis we arrive at size of 160 feet span, which on a normal biplane design gives an all-up weight of 45,000 lbs.

Even if it is possible to exceed this limit the next condition—freedom of action—rather rules out further increase in size by reason of the necessity for suitable aerodromes, shed accommodation, facilities for repairs, which would naturally be fewer even on a country's own territory.

Secondly there is the question of large aeroplanes for civil transport. Here one must assume that the pay load warrants the increase in size or alternatively that the range is correspondingly raised by additional fuel load. The limits imposed by construction difficulties under war conditions are not operative, but the limitations of aerodrome accommodation, etc., still influence the question. Aerodrome surface would need to be specially prepared to deal with the effect of large heavily-loaded undercarriage wheels and to allow for rapid acceleration to facilitate take off. Hangar accommodation becomes an important item of capital expenditure, although it is realised the type would have to be designed to allow safe pegging down in the open and prolonged exposure to all weathers. Force landing grounds I have not taken into account as our future designs must allow for failure of one power unit without necessity for this liability.

Reverting to the large flying boat, the general limits outlined for the corresponding aeroplane disappear for both military and civil types. Aerodromes—or shall we say suitable alighting waters?—are available in all natural harbours, sheltered waters, estuaries, certain rivers and lakes. Construction can be carried out at any suitable waterside where the necessary engineering shops and slipways are available. The size of flying boats can be increased with confidence as design develops, especially as seaworthiness increases as with ordinary seacraft.

An analogy can be made between the two old forms of mechanical transport —rail and steamship; land aircraft and flying boats—in many respects, but especially in the nature of the limits discussed above.

To forecast the future size or weight of flying boats is rather futile when one realises that even a quarter of a century, through some radical alteration in production of mechanical power, may change the whole aspect and limits of flying.

One can gauge, however, the present trend from my next chart, No. 15, on which have been plotted the spans and all weights of modern flying boats over 10,000 lbs., together with available data of large bombing aircraft. The outstanding point of this chart is the super flying boat now under construction by Dornier.

In conclusion, I find no reason to suppose that any of these large types will gain relatively over existing types because of size alone. In other words, increase of size, increase of power, will proportionately increase load or range, but anything beyond this must be attained by the skill of the aeronautical engineer in construction and design on the lines I have put before you this evening.

Discussion

Major J. S. Buchanan: Like all the other members present that evening, he regretted very much that Major Barlow had "hedged" on the original intention of the Council, which was to have a paper on the influence of size on the weight of aircraft. That would have resulted in the most interesting discussion the Society had had for years. In spite of that, the lecturer was to be congratulated on having produced an excellent paper on a very difficult subject, full of pitfalls, and upon which it was nearly impossible to generalise without subjecting oneself to considerable criticism.

He would deal as shortly as possible with the points he had to raise. The lecturer had asked them to cut out all the reference to propeller efficiency. But in making the charts no doubt he had a propeller efficiency in mind, and the speaker wondered what it was. One assumption that the lecturer made, on the same page, was the loading per square foot on the planes. Here, as the speaker read it, the loading per square foot on the small fast machine was 14 lbs., and on the relatively slow 10 lbs. Why this differentiation? The assumption was also made that the air-cooled engine had a higher consumption than the water-cooled engine. In America, he was informed, one of the air services had decided to abandon water-cooled engines because, in addition to other reasons, it had been found that the air-cooled engine had a better petrol consumption than the water-cooled type. Our engine designers might think hard on that subject.

The analysis of the effect of load factors on total weight was extraordinarily interesting, and he thought the results were very similar to those put forward by Pippard some years ago in a paper to the Aeronautical Research Committee. The question of load factors on aircraft was much in discussion at the present moment, and it looked as if the weakest point in a fast machine was not the aircraft structure itself, but the structure of the human frame. We were reaching a stage where the aircraft was actually stronger than the pilot.

He was disappointed that nothing was said about the influence of floats, and how they would be expected to vary in weight with size. He was not sure of the correctness of the conclusion as regards propellers. Major Barlow assumed that the only way to lighten propellers was to make them of magnesium alloys. The speaker hoped and believed that it would be possible to make lighter propellers without being limited to an alloy which at the present time was subject to so many serious disadvantages.

On the question of tanks, the lecturer had given a very nice curve on the variation of tank weight with size, but the speaker would like to know what shape of tank he had assumed. At the end of the paper he dealt with the influence of size on weight, but the present speaker did not propose to step in where the lecturer himself had not the courage to tread.

Major J. Ledeboer: There were two points he desired to stress. In the lecturer's weight analyses for such things as tanks as well as for aluminium structures, it seemed to him that Major Barlow had lost sight of one very important point, namely, the increased sections that one had to use in the case of a highly corrodible alloy such as aluminium in order to guard against the effects of corrosion, which nowadays, at any rate, did not exist in the case of stainless steel. His second point was that he did not think the lecturer had sufficiently taken into account the factor of durability or reliability. In fact, upon that point he had said nothing at all. Every aircraft user, as apart from every aircraft designer, would agree that a loss of performance corresponding to, say, two or three miles an hour was infinitely preferable to a decrease of, it might be, 10 per cent. in durability. Again, a factor which he did not seem

not have taken into consideration in considering the size of flying boats was the very important one of take-off. At the present moment our knowledge of the properties which conduced to reasonably good take-off for a flying boat was very slight. He hoped that in the near future some definite information would be forthcoming on that point. The lecturer would find that the problem of take-off of a very large flying boat might present difficulties in varying conditions of wind and water which possibly Dornier had not yet fully realised in designing his very large flying boat.

Mr. F. HANDLEY PAGE: He was rather afraid to speak on this question of variation of size with weight, because whenever he spoke Major Low always contradicted him! In this paper he thought the lecturer made some rather false comparisons. He spoke of the comparison between a flying boat and a large aeroplane. He said that, of course, in the case of the latter one had large aerodromes and large hangars, but that when one came to the flying boat one did not need these at all; the flying boat was put down in its natural harbour, and apparently was built on the water, floating all the time. But it seemed to the speaker that if one was going to make and operate a land aeroplane under the same conditions as one gave to the boat seaplane, there was nothing to choose between the one and the other.

A good many of the lecturer's comparisons were not strictly true. It was sometimes misleading to take analogies. Take the analogy between the steamship and the railway. The two things were not really analogous. The road over which the steamship went was provided by the water and cost nothing. On the other hand, the railway had to lay down a special track, and a great deal of the cost of running the railway was the cost of the road-bed. The size of the railway cars was limited by the track over which they went; there was no such limitation in the case of the steamship. Exactly the same condition applied in the air. One was travelling in a medium in which there was no limitation of size. Therefore he thought it held good for both land and sea machines that, travelling in the air, one could build machines in either case equally large.

There were one or two questions he would like to ask the lecturer. The lecturer stated that there was a definite physical fact which placed the air-cooled resistance figure of engines of the power under consideration at approximately 1½ sq. ft. higher than the water-cooled power unit. The speaker always rather distrusted *cæ cathedra* statements by whomsoever made, and he would like to know what that exactly meant and upon what it was based.

He was very pleased to see the curve in Fig. 3, in which the lecturer showed the complete inconsistency of the Air Ministry in laying down their load factors.

The next point was with regard to the use of duralumin for pipe lines in the power system. The lecturer showed the great advantage from the weight saving point of view of using duralumin. Probably the advantage in weight was a factor which might be supposed to favour duralumin piping when submitting estimates to the Air Ministry, but the same favourable opinion might not be held after it had been in use for some time.

It was about twelve years ago since the speaker read a paper on the influence of size on weight, and it was interesting to observe the change of view which had now taken place. People now believed that machines could be built to bear a considerable amount of weight, but on the occasion of his own paper there was a good deal of jeering at the possibility of the large aeroplane. In the intervening years, evidently, a good many people had been converted.

Mr. C. R. FAIREY: He could sum up his opinions on the weight of aircraft by saying that he was "against it." But he thought the various points of Major Barlow's paper really came down to the same thing, that they were

saddled with the definite fact that about one-third of the flying machine was structure weight, and there did not seem to be much possibility of escape from this with existing materials. Whatever the type variations, the figure remained at between 27 and 35 per cent., and it looked as if they were approaching the limit which they must put up with. Now that they were coming on to the use of metals it was not for them but for the metallurgist to show a way out. He did not know—nor was he aware that anybody knew—why a particular steel or alloy of steel had a tensile strength of, say, 75 tons to the square inch, or why a particular light alloy had a specific gravity of 2.2. But did the metallurgist know? Could he tell them if there was any possibility of getting a reasonably non-corroding light alloy of a specific gravity of 1 or less, or a steel of 100, 200, or even greater strength? It was necessary to wait for the physicist or the metallurgist to give them better materials before they could see any great advance from the point of weight of aircraft itself. When this came about the big machines could become still bigger ones, but the relationship to the smaller machines would remain. The possible lightness of aircraft was now reaching its limit, and for immediate further improvement head resistance must be reduced and power increased.

Major G. P. Bulman: He wished that someone much more competent in engine design than himself were present in that capacity to pay a tribute to Major Barlow for setting out so clearly the various points which the engine designer must take into account in reaching that compromise which was the root of all sound engineering practice. Major Barlow had shown that the old idea of mere weight per horse power being the sole criterion of performance was rapidly giving place to relative head resistance and fuel consumption. He had referred in the matter of reducing weight to the need for higher speed and suggested that 3,000 r.p.m. was not too high to hope for. The speaker thought he had placed his figure rather too low, and that in quite the near future such a speed would be common, not perhaps in engines already well known in service, but in those which were looked for to come.

He was in entire agreement with Major Barlow that the use of magnesium was a thing which they had to press very hard, at any rate in engine construction, whatever might be the case for aircraft. Undoubtedly here they had been rather too impressed with test-pieces which might be quite representative of aircraft conditions but certainly did not represent engines. Some of the delay and difficulty which had been associated with magnesium work here for engines was perhaps attributable to the constructors themselves in that they had sent off to the foundry any old pattern which they happened to have lying about and not required for ordinary work, and further, had left the negotiations as to supply specification of requirements, tests, etc., to be handled by routine, instead of regarding it as a development needing direct supervision. He had reason to believe that in certain quarters every encouragement was being given now to magnesium introduction into aero-engine construction. In the matter of fuel consumption Major Barlow had a legitimate gibe at type-test figures. The speaker would point out, however, that the type-test consumption was based on a 100-hour run, of which 99 hours was at nine-tenths power, so that the resultant figure was not for an all-out power. The curve given for normal average consumption was not entirely up to date. Actually the present figures were somewhere in between the two shown. A type-test was recently completed on a water-cooled engine at 0.485 lbs. per h.p. hour, which was a good deal lower than as stated in the paper. The speaker thought it not unwise to discourage in type-tests the taking of ultra-low consumptions, which would be purely misleading when applied to actual flight conditions, where accurate flow meters, very carefully controlled temperature, and very skilled observation, could not be provided. Consumption, too, as they knew it to-day, was largely a function of distribution, and one had to cater, not only for normal running

of the engine, but quick acceleration, particularly for certain types of military aircraft. That factor was being dealt with in recent design by the introduction of an auxiliary system, by which, at the moment of acceleration, the additional quantity of petrol required was forthcoming, and when the need for it was passed—the engine running normally—the consumption returned to that which was simply adequate at the particular speed.

Mr. P. A. RALLI: He would like to point out that the advantage as between steel and duralumin for tank and other construction varied with the degree of stressing. When a material was fully stressed the respective advantages as between one material and another came to considerably less.

Mr. M. L. BRANSON: He felt himself entirely incompetent to deal with this very involved problem of the influence of weight on size or *vice versa*, but there were one or two little details on which the lecturer had touched and on which he would like to ask him a question. Major Barlow had said that there was a definite physical fact which placed the air-cooled resistance figure of engines of the power under consideration at approximately 1½ sq. ft. higher than the water-cooled power unit. The resistance due to cooling an engine, the speaker thought he was right in saying, could be divided into two parts, that which must be caused by having, so to speak, to pump air past certain surfaces, and that which was caused by the shape of the parts, whether radiator or cylinders, which have to be exposed to the airstream. With regard to the first of these resistances, that due to having to pump air past certain surfaces, there was no particular inherent reason why that should be greater in the air-cooled engine than in the water-cooled engine. The difference of temperature between the air and the surfaces it had to cool was greater in the case of the air-cooled engine than in the radiator of a water-cooled engine, and the radiator must have greater surface, and therefore greater friction. If, therefore, the "physical fact" to which the lecturer referred related merely to the difference in shape between the air-cooled and the water-cooled engine, plus radiator, he must be assuming that the shape now associated with air-cooled engines was inherent in them. The speaker did not think that this was so. Attempts were now being made at the construction of axially arranged air-cooled engines. Furthermore, there was the possibility of cooling an air-cooled engine by having enclosed passages through which air was pumped exactly as if it were water.

A further question he would like to ask was as to why air-cooled engines should consume more petrol. Was this an inherent property, and, if it was, what was the reason? One would think that as the temperature of the cylinder walls was generally higher there might be a possibility of getting higher thermal efficiency than was obtainable with water-cooled engines. He believed there was some difficulty as to the high compression ratio, which could be used with safety in the case of water-cooled engines, but not in the case of the air-cooled engines. With improvement in the methods of cooling air-cooled engines, however, that might be overcome.

Mr. W. D. DOUGLAS: He would like to ask Major Barlow what exactly was meant by the statement in the paper that "fatigue in properly seasoned wood is unknown." Taken in conjunction with the previous interesting information as to the reason why M. Fokker still retained wood construction for his monoplane wings as opposed to steel or light alloy construction, one might conclude that fatigue phenomena could not occur in properly seasoned wood. This did not quite agree with general experience. In a recent book by Moore and Kommers on "Fatigue of Metals," one chapter is devoted to "Fatigue of Timber," and contains some information on the effect of alternating stresses on properly seasoned wood. He (the speaker) had had a part in some further tests made for the Air Ministry, and it was interesting to find that timber subjected to alternating compression and tension behaves somewhat like

metals—that is to say, eventually a fatigue crack forms at a stress equal to about half the static compression strength of the timber. This occurred with well seasoned spruce. The speaker did not, however, wish to suggest that fatigue phenomena were likely to give much trouble in aircraft, only that it was advisable to remember that they could occur. It could not be stated definitely that accidents had not occurred owing to fatigue cracks. In the examination of accidents, fatigue fractures may have escaped identification owing to lack of information as to their characteristic appearance. Fractures had occurred in the air due to fatigue, but in these cases the primary cause was some conjunction of other circumstances which occasioned the fluctuating or alternating stresses in the part, so that the occurrence of these fractures did not mean that fatigue was a likely source of danger with timber construction. It did, however, seem a little bit dangerous to assert definitely that fatigue in properly seasoned wood was unknown.

Flight-Lieut. P. W. S. Bulman: He considered, in connection with the supercharged engine, that there had been a much greater saving in weight than the lecturer had stated. Supposing one could supercharge an engine to, say, 15,000 ft., this being an increase in h.p. equivalent to more than 20 per cent., he thought he was right in saying that the increase in weight was of the order of 5 per cent. He felt that whilst progress in improved materials must necessarily be slow, more immediate returns were to be looked for in the saving of head resistance and the obtaining of an improvement in thrust from a given horse power. In one part of his lecture Major Barlow showed a curve of petrol consumptions which went to indicate that engines of to-day were more economical than a few years ago. He would like to ask Major Barlow whether these consumptions—presumably taken in the air—were made with a carburettor which was not hand-tuned in any way. He was inclined to believe that the results were obtained by careful hand-tuning of the engine, and would approach the more economical curve which Major Barlow had exhibited.

Captain Sayers: Fig. 1 in the paper showed for given classes of aeroplanes a linear relationship between increment of weight and the equivalent of flat plate resistance. That linear relationship implied that the lift/drag ratio of the machine remained constant, in spite of the fact that one had added 3 sq. ft. of head resistance to it. These curves could not be linear. Major Barlow appeared to have assumed that the l/d ratio remained constant, or was it possible that the curve had some other meaning? He would like to repeat the question already asked in that discussion, as to what was the "definite physical fact" which placed the air-cooled resistance figure of engines at approximately 1½ sq. ft. higher than the water-cooled power unit. He knew, in fact, that the average air-cooled engine had higher resistance than the water-cooled engine, but he was convinced that it could be made smaller than the figure given.

Dr. Thurston: The paper demonstrated the methods used by the practical engineer in solving the most intricate problems, and it did so by using charts which, as it were, summed up the massed experience on a particular problem. Any fool can tell when an aeroplane was too weak, but it took an extremely clever man to tell when an aeroplane was too strong. It was only by careful examination of data that parts which were too strong came to light. Whether aeroplanes would ever be weightless, he did not know, but obviously that was the thing designers were aiming at.

He thought it was time that the factors of safety, or load factors, were thoroughly overhauled. At present there was a factor of safety, or load factor, which applied to the whole machine, whereas it would be much better if the factor of safety were limited to each particular part. For example, the front top spar might have a certain factor of safety, but there was no need to have the bottom front spar with the same factor, as an experience of his own during

the war, when the bottom front spar was shot through at the point of inflection, bore out. The load factor could be varied from point to point in the spar, and the load factors about the machine could be varied, because it was certainly not necessary to have the load factors now in vogue on many of the parts. He spoke feelingly, because it fell to him to fix the load factors for military machines during the war. The larger the machine the smaller the load factor or factor of safety required, but there was no need whatever for the inconsistencies shown in the diagram, and certainly no need now to have standard load factors applying to every portion of the machine when a better system could be forthcoming. The value of the graphical method was extremely well shown in the paper. This brought out the value of chart analysis on the basis that the existing data were standard. If air-cooled engines or water-cooled engines were not standard the prophecy therein given was valueless, and he ventured to suggest that the direction of development with air-cooled engines was such that there was a great deal more to be said in favour of air-cooled engines than even that prophecy would suggest. Obviously the air resistance of air-cooled engines could be very greatly reduced per h.p., and that would give them a superiority very greatly in advance of the water-cooled engines.

Major BUMPUS: In the many discussions which had taken place on the weight of aircraft, emphasis had been laid on the importance of closely studying the increase of loads involved with increase of size of similar structures, the assumption usually being that it was permissible to work to the same stresses in large as in small machines. The problem of the large machine was, however, made more difficult since the question of deflection came in, especially in monoplanes, and rendered it necessary to put in more material to retain reasonable stiffness in the wings.

With regard to airscrews, it would be unfortunate if one could look only to the development of magnesium alloys to get any saving in weight in this direction. The manufacturers of steel airscrews had so far used mild steel, and it might be hoped that high grade steel blades would be developed, and it appeared likely that the use of light alloy blades of sheet construction might affect a material saving in weight.

Mr. J. D. NORTH (*communicated*): In sending these few observations to the discussion it has not been possible to give the paper the attention which it deserves.

Fig. 1 seems very startling. Surely the curves can only be linear for comparatively small increments in weight? The actual magnitudes of the weights and equivalent flat plate ratios are startling and, if they are understood correctly, do not appear to accord with ordinary practice or the results of previous analyses on the same lines. It would be interesting to know exactly how these curves have been arrived at.

The writer is in considerable disagreement with what Major Barlow has to say on the subject of fatigue. The suggestion that in aircraft construction all new materials must be reviewed for their claims to lightness in association with their fatigue limits appears misleading, insomuch as in only a comparatively small proportion of the aircraft structure does the question of fatigue range of materials enter into the problem, unless there is bad design. He would suggest that Mr. Fokker's reasons for retaining wood construction might be quite as properly described as due to inertia as to fatigue. Actually, of course, in cantilever wing construction the adaptability of wood to varying sections and scantlings is of great assistance. It is true that the fatigue range of aluminium alloys is low in relation to the ultimate compared with steels, but many apparent fatigue failures in aluminium alloy are associated with ductility, work hardening and homogeneity and are not properly fatigue failures at all,

insomuch as the aluminium alloy parts may be replaced by steel of a lower absolute fatigue range with more satisfactory results.

The statement quoted by the Materials Division of the Air Corps of the United States about the specific fatigue strength of aluminium alloy, ordinary high grade steel and heat treated chrome-molybdenum steel, to have a precise significance seems to require some statement as to what is meant by "ordinary high grade steel," and more information as to the state of the heat treated chrome-molybdenum. If these figures were expressed in the usual manner as the ratio of the fatigue range to the ultimate tensile strength, it appears they would throw more light on the question.

In regard to the comparisons which are given in the paper, the weight ratios and the stiffness ratios for spars depend to a considerable extent on the loading conditions selected or the constants chosen. It does not seem that one can safely say more than that the weight ratio table places the various materials of construction in their correct order of merit from a weight point of view. The variations in stiffness ratio are of course those inherent in the use of materials having approximately uniform specific coefficients of elasticity and with varying specific allowable stresses, resilience is not disadvantageous. Apropos allowable stresses:—The 65 tons per square inch proof stress is actually an arbitrary inspection figure for the material and is not associated with the maximum allowable stress which may be considerably higher on material having just the bare properties of the specification.

The weight figures given for fuel and oil tanks are particularly interesting and the advantages to be gained by the use of a duralumin tank from a weight point of view are well brought out. It is noted that the method of construction used for the duralumin tank is nickel coating and soldering. Experiments were tried on the nickel coating of duralumin some years ago by the writer and the conclusion was arrived at that adhesion was not too reliable. It would be interesting to know whether such tanks have shown themselves completely satisfactory from a corrosion standpoint, a matter which might be more important in the water system than in the fuel system.

On the subject of pipe lines, is Major Barlow satisfied that the failure of duralumin to reach the standard of reliability in service of aluminium or copper is due to its low resistance to fatigue? The statement which he makes as to the relative reliability of these materials is completely agreed with, but the exact causes of the failure of duralumin in this respect require investigation. Any information Major Barlow can give will be extremely helpful.

Major Barlow gives a comparison of the weights of wood, steel and duralumin propellers. One would expect that this comparison would be much affected by the order of importance of bending and "centrifugal" stresses. If these figures are for a high speed direct drive engine, presumably the hollow steel propeller would show up very much better on a geared engine. The general conclusion with regard to the effect of gearing seems to be that the metal propeller on weight grounds compares very unfavourably with the wooden propeller where geared engines are used. Possibly with these engines we may have to reconsider methods of manufacturing metal propellers, if indeed wood must be definitely excluded.

Major Barlow arrives at the conclusion that the maximum possible range of 10,000 miles is obtainable by going to a weight of 50,000 lbs. and that this weight is the most favourable for obtaining high range. It appears that this surprising conclusion is due to the assumption that structure weight percentage is independent of size; if so, it is difficult to bring this into line with the theory of scale.

On the subject of magnesium, Major Barlow says, "There is evidence that slight variations in the aluminium content of the alloy is an improvement in

resistance to this defect" (*i.e.*, corrosion). It appears that there has been some error in transcription here. Does Major Barlow mean that in the magnesium-aluminium-manganese alloy the aluminium content is critical or the aluminium-manganese ratio? Can we have details of or references to the evidence?

Mr. J. D. FRIER (*communicated*): In this very interesting paper, the author has laid stress on a number of points which in the ordinary way receive scant attention in routine design.

Generally, it is true to say that the effect of weight on performance has always been a subject of investigation, and in the paper the author has given this his first care.

Designers have, in the past, been able to examine the effect of weight increases on performance from a consideration of a simple expression representing horse-power required for flight, viz.,

$$550\,P = \rho V^3 (W k_D / w + R) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

An increase in P corresponding to increases in W and R then follows, for if the top speed is the same, k_D remains unaltered, while for the same stalling speed an increase in area is required which makes w constant, hence

$$\delta P = (k_D / w)\,\delta W + \delta R$$

whence, for no increase of power,

$$\delta W / \delta R = -w / k_D \quad . \quad . \quad . \quad . \quad . \quad (2)$$

In a given case, therefore, the effect of weight on resistance and therefore on performance could be estimated. Notable examples of investigation on the above lines are well known.*

In the present case the author has reduced the weight increments to equivalent frontal areas which expresses equation (2) in a more practical form.

With regard to airscrew weights, Fig. 12 of the paper is very instructive, showing as it does in a very clear manner the effect of airscrew rotational speed on its weight.

A very large amount of labour has been involved in the preparation of the paper and Major Barlow has earned the sincere thanks of the Society for his valuable contribution to its proceedings.

The PRESIDENT: To add one more to the host of questions which had been addressed to Major Barlow, he would like to ask why in dealing with construction of fuel tanks he had not taken into consideration a tank employing neither rivetting nor soldering. It would be interesting to see the comparative figures.

REPLY TO THE DISCUSSION

Major BARLOW: The Chairman has drawn my attention to a type of tank not yet in practical use in this country. Such a method of construction as suggested by him should produce a tank lighter than those shown in the charts. Further details of this new design would be extremely interesting.

Major Buchanan raised the question of propeller efficiency. This was varied from 69 to 80 per cent., according to type; the loadings assumed corresponded to the landing speeds and speed ranges of the types of aircraft under analysis. His remarks about consumption of air-cooled engines being found definitely lower than the water-cooled type in the United States is something entirely new and as far as I know is not being confirmed by publication of official data. I venture to say the reason for the adoption of the air-cooled engine in certain types to a greater degree in the States is for other reasons than this and is possibly wrapped

* For example
G. T. R. Hill, R. and M. 217.
J. D. North, International Air Congress, 1923.

up with manufacture and production. There is no data in England which supports this contention and in my experience it does not occur in actual practice although there may be freak conditions found on the bench test.

The average figures for two well-known water-cooled types vary from 0.49 to 0.51 pints per b.h.p. hour, for air-cooled 0.516 to 0.6 pints on standard service fuel.

With reference to the tank weights. These are based on a complete series ranging from small oval shape to larger types, all of similar section. I find that it is possible to keep to this weight curve for tanks for all normal designs.

Major Ledeboer, I think, is looking "backwards" and not "forwards" in submitting to loss of performance in modern design. There are many methods of resisting corrosion and no designer would dream of tackling the problem as suggested by him, that is, adding weight to allow it to corrode away with time. High performance and efficient aircraft need not mean in any way a less durable type.

Mr. Handley Page rather disputes my analogy of the railway and steamship. I agree with him that the medium (air) is naturally the same for both land and sea types of aircraft and has no effect on the limitation of size, but as the speaker confirms, there is ground equipment in the case of the railway, which does limit in size that means of transport. Once a flying boat is built and launched, I foresee it operated in a similar manner to a boat or steamship having the same water space and dock facilities.

In the case of land aircraft, aerodrome conditions, hangar spaces, and all other incidentals limiting such a landing ground do have an effect on the size of land aircraft to be operated.

Major Bulman's remarks I note with great interest, as I feel sure that this question of fuel consumption is now receiving attention from carburetter and engine designers. This state of affairs has arisen with the development of larger machines and specifications requiring longer range, both of which are important features of the development of civil air transport.

Flight Lieutenant Bulman raised a practical flying point in the run of aero engines with the greatest economy. The figures quoted are for standard carburetters with mixture or lever control independent of the throttle. With the advent of the really reliable flowmeter there is no reason why all engine types should not be run with considerable improvement in consumption, at any rate such practical tests would aid the solving of many carburetter and distribution problems and aid much towards reduction of all up weight of aircraft for a given range.

Mr. W. D. Douglas criticises my view of fatigue in properly seasoned wood. For this I am taking practical experience in aircraft, not laboratory tests. A wooden structure, by its very nature, absorbs any vibration such as might occur in normal aircraft structure design, that is to say, it is almost impossible for any particular wooden part to be able to be subjected to a fatigue stress as would cause fracture. The statement, I admit, might read better if qualified by this addition. I can find no evidence of failure in timber in any aircraft due solely to normal vibrations. Naturally, if some other part fails and excessive vibration such as flutter commences, a different problem arises at once.

Mr. North and Captain Sayers discussed the w[illegible] resistance curves. These are linear and for comparatively small increments, as explained when showing the graphs on the screen. The calculations are rather too lengthy to publish in reply, but at a later date I hope to communicate them to the Society. Dealing with the fatigue question for steels, the ordinary high grade steel has an ultimate of 42.5 tons/sq. in. and the heat treated chrome-molybdenum 78 tons/sq. inch.

Nickel coated duralumin tanks have stood extraordinarily well in service, but I do not think they resist corrosion so well as an anodically treated aluminium or an aluminium tank treated with tung oil varnish.

The failure of duralumin pipe is due mainly to material defects which show up after such pipes have been subject to vibration.

Mr. North specially draws attention to my conclusion that structure weight is independent of size. Careful analyses of many aircraft show that with present conditions—aerodynamic and limitation of the existing power units this is correct, within the usual limits. Our weight percentage reduction of structure by increased size is relatively small, in fact such variation is within the limits of type design.

I thank Mr. North for drawing my attention to the loose wording concerning magnesium alloy and effect of aluminium as regards corrosion. Both the amount of aluminium and manganese are critical for corrosion effect. Manganese should be linked up with the aluminium content. As Mr. North is no doubt aware, research work on this subject is in progress at the moment in England, but there is an excellent paper on the subject, "The Corrosion of Magnesium and of the Magnesium Aluminium Alloys containing Manganese," by J. A. Boyer, Report No. 248, N.A.C.A., 1926.

Several speakers have pulled me up on one of my statements concerning air-cooled engines—the resistance of this type compared with water-cooled engines. A full reply would necessitate a lecture in itself on this controversy. May I remind the exponents of the air-cooled that there is a field for both types, but for speed this fact of additional resistance for equivalent thrust horse-power quite definitely places the water-cooled in front. Practical proof is given by the highest speed aircraft now in existence.

A water-cooled engine may be cowled into almost a perfect streamline shape. Every air-cooled, whether of the usual radial type or in line, must have each cylinder head exposed to sufficient air stream to give efficient cooling. I agree that to the resistance of the water-cooled engine must be added that of the radiator, but by design this by its position and construction can be made an addition which still leaves the final equivalent resistance well below that of the air-cooled to the extent of the figure quoted in the paper, $1\frac{1}{2}$ sq. ft., which should be specially noted refers to types of 450 normal b.h.p. All model wind channel tests confirm that there is a definite difference between the types. Perhaps the speakers object to the "physical" side of the fact. I take it as the difference between "rough" and "smooth." Further, I am quite sure if nature ever intended a "starfish" to fly, it would not be end on.

The meeting concluded with a hearty vote of thanks to Major Barlow, proposed by the CHAIRMAN.

PROCEEDINGS

THIRD MEETING, SECOND HALF, 64TH SESSION

In the Chair: Mr. L. H. HOUNSFIELD (President of the Institution of Automobile Engineers)

AIR-COOLED ENGINES IN SERVICE

BY

A. H. R. FEDDEN (Fellow)

A joint meeting of the Royal Aeronautical Society and the Institution of Automobile Engineers was held at the Royal Society of Arts, London, on Thursday, February 14.

Colonel THE MASTER OF SEMPILL (President of the Royal Aeronautical Society): This was the third joint meeting with the Institution of Automobile Engineers this Session, and he was glad to say that Mr. Hounsfield, the President of the Institution of Automobile Engineers, had consented to take the chair out of compliment to Mr. Fedden, who had been a distinguished designer in the motor car world before he became one of the most brilliant designers of aircraft engines. Mr. Fedden had been for ten years chief designer to the Bristol Company, and had been responsible for the design of the many engines produced by that Company. The Jupiter engine was, no doubt, the best known to most of them and was being constructed under license in 11 foreign countries. That was a very considerable tribute to the designing genius of Mr. Fedden. The foreign countries which had taken up this engine were constructing it in considerable quantities for military and civil purposes. We ourselves were using this type of engine in large quantities in military and civil aircraft. Jupiter engines were in use on the Cairo-Bazra service, and the returns showed that 100 per cent. of the service scheduled was accomplished. The Director of Civil Aviation in the U.S.A., who was to have been present at this meeting, had stated that he attributed in large measure the success of the air transport companies in America to the use of air-cooled engines following on the scrapping of water-cooled engines, and that he visualised the time when air-cooled engines would be used universally in American air transport concerns. From the automobile point of view, the picture was quite a different one, and the well known and successful Franklin car was the only example of a car with an air-cooled engine. Those who had been able to read an advance copy of Mr. Fedden's paper would see that he lamented the fact that although there were a vast number of Jupiter engines in service in the Royal Air Force, he was not able to present data of the running of these engines. It seemed very unfortunate that there was this difficulty of obtaining data from the R.A.F., because that data would be of the utmost possible value to Mr. Fedden and to other designers and users of air-cooled engines. It was to be hoped that Mr. Fedden would be able to publish an appendix to the paper later giving data relating to the engines that are actually running and in the R.A.F. to-day.

I. Introduction

It is now rather more than three years since I last had the honour of presenting a paper before this Society dealing with air-cooled aero engines. At that time the air-cooled engine had not fully won a place "in the sun," which may be fairly stated to be the case to-day.

For some years after the war there was a considerable aversion towards the air-cooled aero engine owing to certain types which had been developed during the war which were supposedly air-cooled, but in reality obtained the greater portion of their cooling by means of exorbitant fuel and oil consumption. As lately as four years ago the practical advantages of the air-cooled engine were only tentatively appreciated by the aircraft constructor, and naturally, owing to his somewhat painful experiences in the past in respect of unreliability and high fuel consumption, it required some missionary work and proof in order to persuade him that the new family of air-cooled engines would really perform in the way their designers claimed for them.

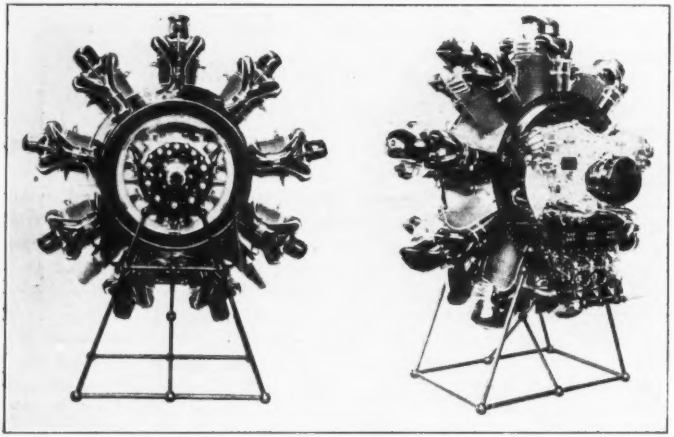

Fig. 1.
The Bristol Jupiter Series VI.
$5\frac{3}{4}$*in. bore,* $7\frac{1}{2}$*in. stroke,* 28.7 *litres capacity,*
440 *b.h.p. at* 1,700 *r.p.m.,* 1.6*lbs. per b.h.p.*

Happily this position has now changed, and it may be safely stated that the proportion of air-cooled aero engines being used for aircraft is daily increasing, and I believe will continue to do so. The fact that the Royal Aeronautical Society has done me the honour of asking me to read a paper on the subject of "Air-Cooled Engines in Service," is, I think, a sufficient proof that this body realises the extent to which the air-cooled engine has now been accepted for all kinds of aircraft.

The change, although gradual, has been really remarkable when it is realised that it is only a little more than four years ago that in-line water-cooled engines were universally used on British and Continental air lines, and that in England at that date there were only a few experimental squadrons of military aircraft using air-cooled motors. To-day a very large proportion of British military aircraft employ air-cooled radials, which are fitted to practically all the single-seater scouts, also to two-seater general purpose aircraft, and to twin-engined bombing machines.

Both in England and on the Continent the change over to air-cooled radial engines for commercial work is equally worthy of notice. I think I am correct in saying that all new aircraft put into Imperial Airways service during the last few years have been fitted with air-cooled radial engines. A considerable proportion of their London-Paris service has air-cooled radial engines, and the whole of their Middle East route, which has been operating with great success between Cairo and Basra for the last two years, employ air-cooled radial engines solely, and the new flying boat service, to start this April between Genoa and Alexandria, with three-engined Short "Calcutta" seaplanes, will also employ this type of engine.

On the Continent the introduction of air-cooled radial engines for commercial aircraft has been almost as complete. The K.L.M. Royal Dutch Air Line, one of the most efficient continental air transport companies, have used air-cooled radials exclusively for the last few years. On their Amsterdam-Paris-London route they have used Fokker machines fitted with air-cooled radial

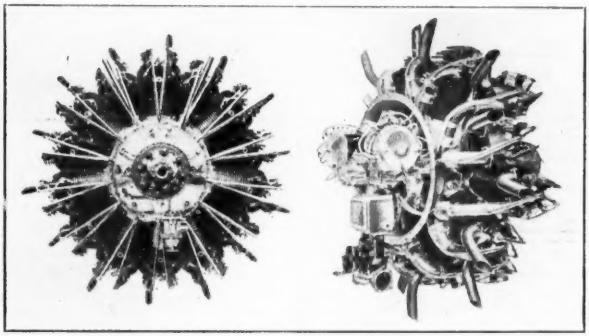

FIG. 2.
The Armstrong Siddeley Jaguar Series IV.
5in. bore, 5¾in. stroke, 24.8 litres capacity,
385 b.h.p. at 1,700 r.p.m., 2.0lbs. per b.h.p.

engines, these aircraft establishing a record for reliability with a corresponding reduction on cost of operation. This transport company also run similar aircraft to Malmo, in Sweden, and their new air line, started in 1928, from Holland to Batavia, in the East Indies, employs aircraft, the power plant of which consists of three air-cooled radial motors.

Similar steps have been taken by air transport companies in France, Germany, and other parts of the Continent, and almost without exception all such air lines have changed over to air-cooled radial-engined aircraft during the last two or three years.

In America the development of the air-cooled radial engine has been almost synonymous with the general rapid growth of aviation. Without exception, the American west to east Atlantic flights have been undertaken with Wright air-cooled radial engines.

All the long distance aircraft from the American coast to the South Sea Islands employed air-cooled radial engines, and that splendid flight of the "Southern Cross" in 1928, from the United States to Australia, was undertaken with three air-cooled radial engines.

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* Joint Meeting with the Institution of Automobile Engineers.

The growth of the light plane movement, which was instituted by the competitive trials at Lympne in 1924 and 1926, was only made possible by the air-cooled engine. The strides made in this development throughout the world have been very rapid indeed, and air-cooled engines have given excellent service in these light aircraft.

Historic long distance flights to Australia, Africa, etc., have been undertaken with these light aircraft and, without exception, the air-cooled engines fitted to them have rendered excellent service.

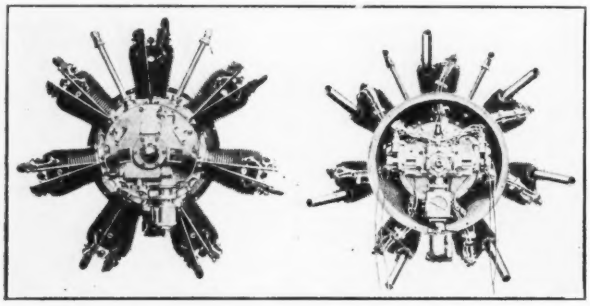


FIG. 3.
The Armstrong Siddeley Lynx Series IV.
5in. bore, 5½in. stroke, 12.4 litres capacity,
180 *b.h.p. at* 1,620 *r.p.m., 2.7lbs. per b.h.p.*

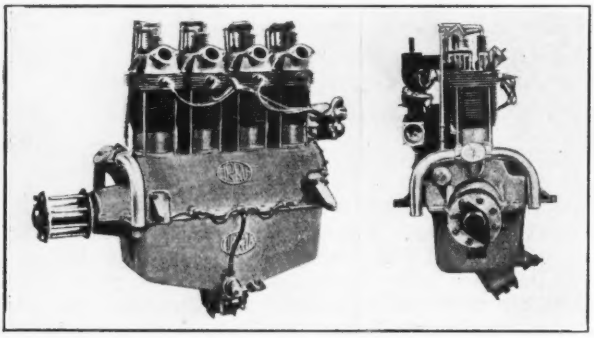


FIG. 4.
The A.D.C. Cirrus, Mark III.
4.33in. bore, 5.12in. stroke, 4.9 litres capacity,
85 *b.h.p. at* 1,900 *r.p.m., 3.3lbs. per b.h.p.*

The result of this very rapid growth in the popularity of the air-cooled motor as a power unit for aircraft has induced a number of new firms to come into the industry.

At the Paris Salon in July, 1928, there were no less than seven new air-cooled engines on exhibition, and a number of famous continental aero engine builders, who previously had "pinned their faith" entirely to the water-cooled in-line motor, came out with new designs of air-cooled engines.

The position at the Chicago Show, in December, 1928, was even more marked in this respect; more than twenty new air-cooled engines were shown at this exhibition.

There are several interesting air-cooled engine designs under experimental development in England to-day, including both radial and in-line types.

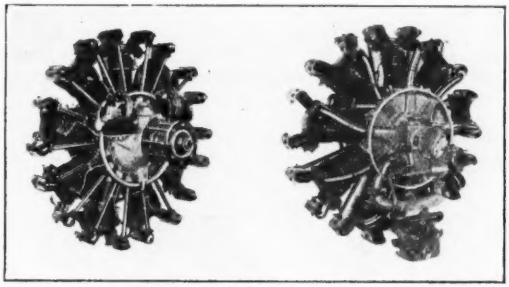


FIG. 5.

The Wright Whirlwind, Mark J.5.

4.5in. bore, 5.5in. stroke, 12.9 litres capacity, 200 b.h.p. at 1,800 r.p.m., 2.5lbs. per b.h.p.

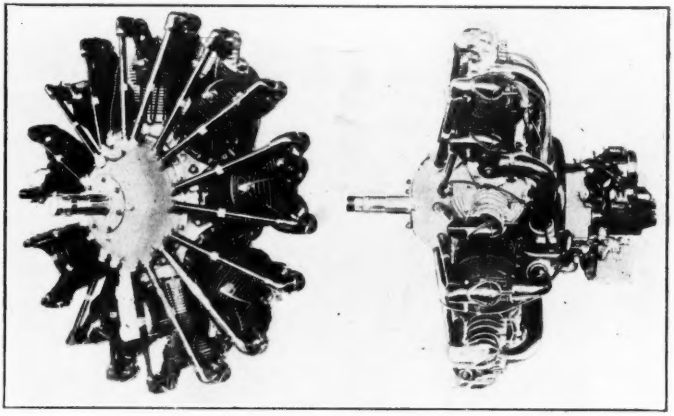


FIG. 6.

The Pratt and Whitney Wasp.

5.75in. bore, 5.75in. stroke, 22 litres capacity, 400 b.h.p. at 1,900 r.p.m., 1.6lbs. per b.h.p.

It will be seen, therefore, that in attempting to give you some information on the question of air-cooled engines in service, there are a large number of motors to choose from, but in order to provide helpful data it is considered that only engines which have been in extensive use over a reasonable period of time

should be seriously considered. The makes coming under this category may, I think, be summed up as follows:—

British—A.D.C. "Cirrus."
,, Armstrong-Siddeley "Jaguar" and "Lynx."
,, Bristol "Jupiter."
American—Wright "Whirlwind."
,, Pratt and Whitney "Wasp."

These engines are undoubtedly familiar to most of you, but to those members of the I.A.E., who may not be so closely in touch with aircraft motors, the Figs. 1—6 will give some idea of their external appearance.

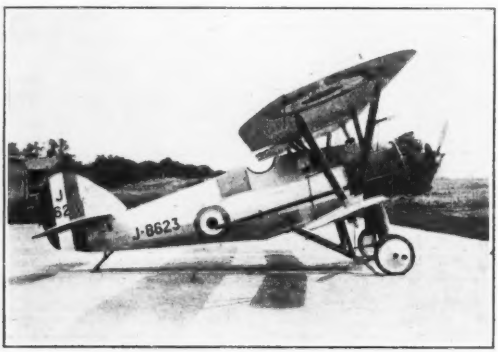


FIG. 7.
The Armstrong Siddeley Siskin.
Single-seater fighter, fitted with Armstrong Siddeley Jaguar supercharged engine.

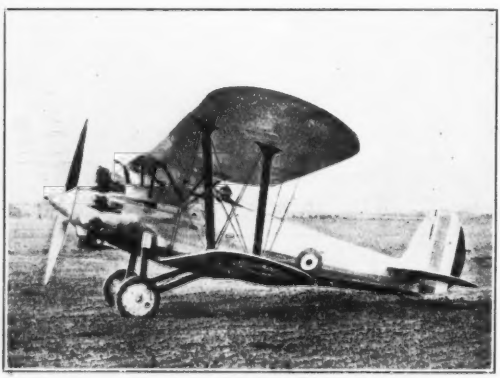


FIG. 8.
The Bristol Bulldog.
Single-seater high altitude fighter, fitted with Bristol Jupiter supercharged engine.

The number of different types of aircraft using air-cooled engines is considerable, and the whole question of the installation of air-cooled engines is an extensive subject in itself which I cannot attempt to go into in any detail in this paper, but before proceeding to deal with the behaviour of these engines in service, I think it will be useful to show to those of my listeners, who may be less familiar with these various types of aircraft, how these engines appear when installed. I am only showing a few (Figs. 7—17) types in production, or coming into production, and will deal first with military aircraft.

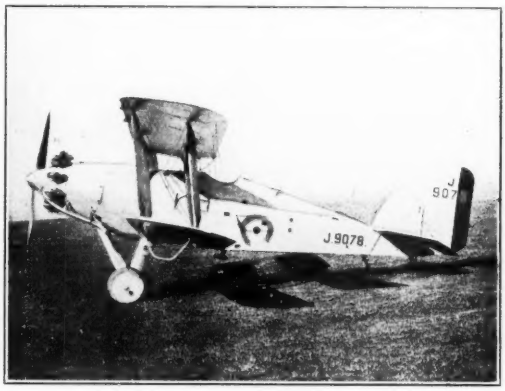


FIG. 9.
The Westland Wapiti.
Two-seater general purpose machine, fitted with Bristol Jupiter engine.

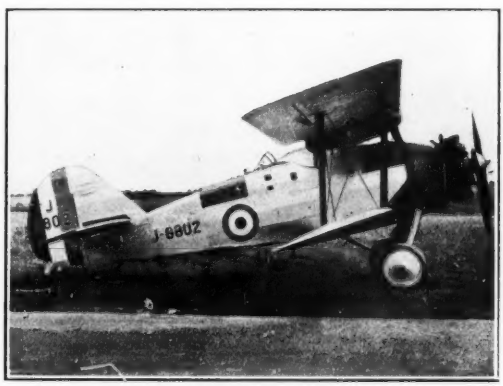


FIG. 10.
Armstrong Siddeley Atlas.
Two-seater Army Co-operation machine, fitted with Armstrong Siddeley Jaguar engine.

II. Service Rendered by Air-Cooled Engines

From my introductory paragraph you will have gathered that during the last four years a very considerable change has come over the type of power unit employed for aircraft, both for military and commercial purposes.

The air-cooled engine, and especially the air-cooled radial, has made considerable strides, and I believe the largest proportion of aircraft are at present engined with air-cooled motors. The air-cooled engine undoubtedly is gaining ground daily, and the fact that the British Air Force has so largely used air-

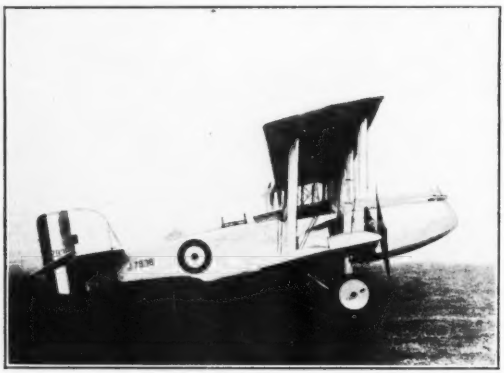


Fig. 11.

Boulton and Paul Sidestrand

Twin-engine high performance day bomber, fitted with Bristol Jupiter engines.

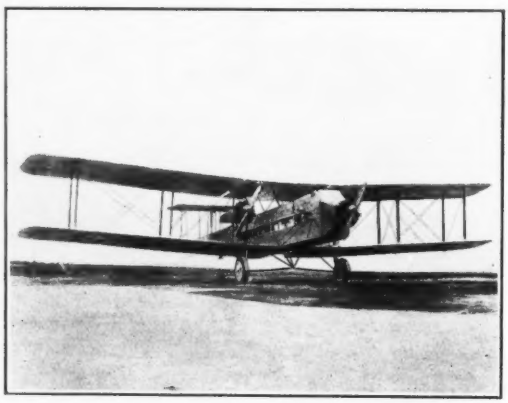


Fig. 12.

Armstrong Siddeley Argosy.

Imperial Airways London-Paris Service, fitted with three Armstrong Siddeley Jaguar engines.

All up weight, 18,000lbs.; seating capacity, crew 2, passengers 20.

FIG. 13.
De Havilland Hercules.
Imperial Airways Middle East Route, fitted with three Bristol Jupiter engines.
All up weight, 15,000lbs.; seating capacity, crew 2, passengers 14.

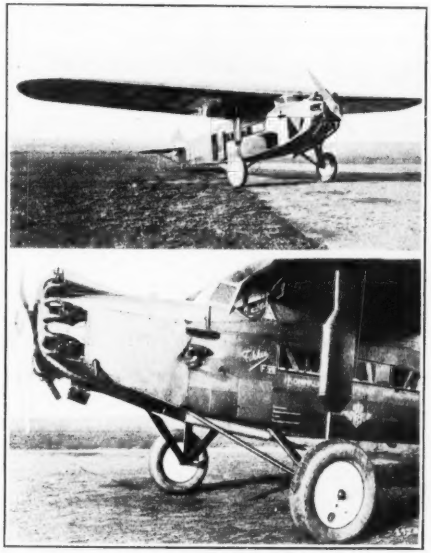


FIG. 14.
Fokker F.VII.
Royal Dutch Air Line, London-Amsterdam-Malmo Service, fitted with Gnome et Rhone built Jupiter engines.
All up weight, 7,900lbs.; seating capacity, crew 2, passengers 8.

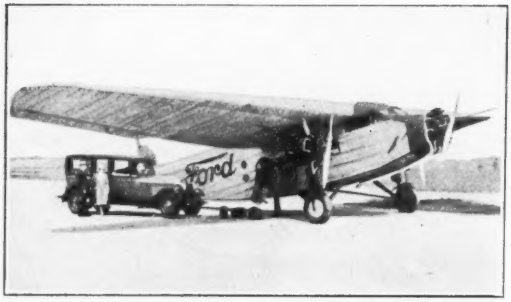


FIG. 15.
American Ford All-Metal Machine.
Stout Air Services, Detroit-Chicago-Buffalo Route,
fitted with three Wright Whirlwind engines.
All up weight, 10,000lbs.; seating capacity, crew 2, passengers 12.

FIG. 16.
Short Flying Boat "Calcutta."
Imperial Airways Genoa-Alexandria Service,
fitted with three Bristol Jupiter engines.
All up weight, 22,500lbs.; seating capacity, crew 3, passengers 15.

FIG. 17.
De Havilland Moth.
Two-seater touring or school aircraft, fitted with Cirrus In-Line engine.

cooled radial motors, and that aircraft operating companies, such as Imperial Airways and the Royal Dutch Air Line, have pinned their faith to air-cooled motors for the last few years and for all their new types of aircraft, is, I think, sufficient evidence that this type of engine is going to be used to a larger extent than ever during the next few years. It is therefore of importance that we should know exactly what service this type of engine is giving at the present time, and what steps should be taken to increase its life and efficiency.

I have been to some considerable pains in an endeavour to obtain accurate service data on the running of air-cooled engines, but my task has not been altogether an easy one. Being interested in one of the types of air-cooled engines described in my category, I have been particularly anxious to be quite dispassionate, and to record as much evidence of other types as possible.

A very considerable number of hours have been flown, and a vast amount of experience gained, with air-cooled radial engines in the Royal Air Force, but this information is unfortunately unavailable.

Some of us have heard rumours of tabulations of the relative reliability of different types of Service engines, and if these rumours are correct it is pleasing to know that the " Jupiter " and " Jaguar " are, at any rate, at the right end of this compilation.

The following figures have been obtained through the kindness of various firms, viz:—

TABLE I.

SERVICE DATA ON BRISTOL JUPITER VI. ENGINES.

DATA FROM IMPERIAL AIRWAYS ON MIDDLE EAST ROUTE.

Number of machines operated	5
Type of machines operated	3-engined De H. Hercules
Number of engines	20
Period covered by data	2 Years
Total hours operation	9280
Average hours operation per engine	468
Maximum recorded hours one engine	960
Average hours between overhaul	400
Average man hours for overhaul—whites Average man hours for overhaul—natives	1356
Average operating r.p.m.	1500
Average fuel consumption, galls per hour	19.7
Average oil consumption, galls. per hour	0.57

This data has been supplied through the courtesy of Mr. Hall, Chief Engineer of Imperial Airways, and relates to 20 Bristol " Jupiter " VI., 420 h.p. engines supplied to Imperial Airways between September and December, 1926, to be fitted into five De Havilland " Hercules " aircraft, for operation on the Cairo-Basra Middle East Air Route.

As is well known history, these aircraft were delivered to the Middle East by air, commencing with Sir Samuel Hoare's famous flight to India in January, 1927.

These machines have been on a weekly service between Cairo and Basra for just over two years, and have flown approximately 300,000 miles.

The *Times* report of January, 1928, giving a record of the first year's working of this service, reported that over 134,000 miles had been flown in 1927 on this route, without engine trouble of any kind, and that the services had been completed to schedule with 100 per cent. efficiency.

I have seen no official report of the records for 1928, but I understand that the route has been operated with equal success during the second year.

Table II. contains data also supplied by Mr. Hall, through the courtesy of Mr. Siddeley, and relates to the Armstrong Siddeley "Jaguar" engines of 385 b.h.p., fitted into the 3-engined Armstrong Siddeley "Argosy" aircraft, for service on the Imperial Airways continental routes.

TABLE II.

SERVICE DATA ON ARMSTRONG SIDDELEY JAGUAR IV.

DATA FROM ARMSTRONG SIDDELEY, LTD., FROM IMPERIAL AIRWAYS SERVICE.

Number of machines operated	
Type of machines operated	3-engined A.S. Argosy
Number of engines	
Period covered by data	
Total hours operation	
Average hours operation per engine	
Maximum recorded hours one engine	
Average hours between overhauls	400
Average man hours for overhaul	480
Average cruising r.p.m.	1625
Average fuel consumption	
Average oil consumption	

Tables III. and IV. contain data supplied through the courtesy of Mr. Guilonard, Chief Engineer of the K.L.M. Royal Dutch Air Line, and relates to 30 Gnome et Rhone "Jupiter" engines, fitted into Fokker aircraft.

TABLE III.

SERVICE DATA ON GNOME ET RHONE JUPITER ENGINES.

DATA FROM K.L.M. ROYAL DUTCH AIR LINE.

Number of machines operated	15	
Number of engines operated	30	
Period covered	3	Years
Total hours operation	25,000	
Average hours operation per engine	830	
Maximum recorded hours on one engine	1,860	
Maximum running one engine in one year	735	Hours
Average hours between overhaul	250	
Overhaul staff, skilled	10	
Overhaul staff, unskilled	27	
Cost per running hour, including maintenance, overhaul and spares	17.5	Shillings
Average operating r.p.m.	1,550	
Average fuel consumption, galls. per hour	20	
Average oil consumption, galls. per hour	0.8	
Man hours for complete overhaul	332	

TABLE IV.

SERVICE DATA ON GNOME ET RHONE JUPITER IV. ENGINES. COLLECTED DATA FROM K.L.M. ROYAL DUTCH AIR LINES ON 11 ENGINES OF 10,120 TOTAL RUNNING HOURS.

Component.	Average life to date. Hours.
Crankcase	1500
Crankshaft	1000
Valve—inlet	1000
Valve—exhaust	650
Valve spring	1500
Valve guides—inlet	615
Valve guides—exhaust	650
Piston	200
Piston ring	165
Scraper ring	270
Cylinder	1500
Main roller bearings	800
Master rod	750
Articulated rods	1500
Gudgeon pins	360

TABLES V. and VI.

These figures have been supplied to me through the courtesy of Mr. Guy Vaughan, Vice-President of the Wright Aeronautical Corporation, Paterson, New Jersey, U.S.A.

TABLE V.

SERVICE DATA ON WRIGHT "WHIRLWIND" ENGINES. DATA FROM NINE DIFFERENT OPERATORS.

Number of engines considered	91	
Total hours' operation	36,464	
Average hours' operation per engine	401	
Maximum recorded hours on one engine	2,000	
Average hours between overhauls	290	
Cost of parts per operating hour	4.3	Shillings
Average operating r.p.m.	1,625	
Average fuel consumption, galls. per hour	11.3	
Average oil consumption, galls. per hour	0.42	

Table V. was compiled from data supplied by nine operators on various types of machines, while Table VI. is a summary of overhaul times on 16 "Whirlwind" motors, used by the Stout Air Services Incorporated.

Table VII. is a tabulation prepared from data collected in the course of a number of overhauls made by the Bristol Company during the last three years.

It relates to the major components, and those most often replaced on "Jupiter" engines, and covers a miscellaneous collection of standard direct drive engines sent in for repair from various sources and different types of aircraft.

In some instances the part has been replaced before the extreme limit of its life was reached, because it was deemed advisable while the engine was dismantled, and for this reason the life of some components will appear to be abnormally short.

TABLE VI.

SERVICE DATA ON WRIGHT "WHIRLWIND" ENGINES.
DATA FROM STOUT AIR SERVICES INCORPORATED.

Motor Number.	First Overhaul Hours.	First Overhaul Minutes.	Second Overhaul Hours.	Second Overhaul Minutes.	Third Overhaul Hours.	Third Overhaul Minutes.	Total Hours.	Total Minutes.
8108	271	30	130	52	—	—	620	17
7317	259	25	336	24	—	—	696	6
8322	150	57	—	—	—	—	310	35
8168	124	50	—	—	—	—	124	50
8169	124	50	—	—	—	—	124	50
7653	188	13	295	40	175	25	714	57
7324	259	25	271	12	—	—	708	12
7655	308	49	338	43	—	—	768	23
7319	259	25	330	44	—	—	652	44
8945	—	—	—	—	—	—	36	45
8946	—	—	—	—	—	—	36	45
8944	—	—	—	—	—	—	36	45
7800	272	35	—	—	—	—	272	35
7654	167	51	349	42	275	54	793	27
8321	256	26	—	—	—	—	256	26
8521	49	47	—	—	—	—	49	47
							6203	24
Average	207	—	293	—	225	—	388	

I realise that such a table is open to misrepresentation, but it is shown for what it is worth, as some such figures are desirable as a guide to the percentage of spare parts that may be carried.

Parts scrapped, which have been written off due to a crash, are not included.

It is somewhat difficult to obtain records of engines operating in the same aircraft over an appreciable period, and I am therefore including the following one relating to "Jupiter" engines, viz.:—

Three "Jupiter" VI. engines, Nos. 6071, 6072 and 6074, were installed in the three-engined Handley Page "Hampstead" in September, 1926, and used on Imperial Airways continental route, and these have been the only engines used in that aircraft since that date.

During the period up to September, 1928, covering two complete years' operation, the engines ran a total of 4,140 hours, or an average of 1,380 hours per engine.

Two complete overhauls were made during this period and, although a number of replacements were naturally made to these engines during the two years, it is interesting to note that, with the exception of one cylinder replaced, the original crankcases, crankshafts, cylinders, connecting rods, and major components were used throughout.

Fig. 18 shows the big-end bush, one piston, one gudgeon pin and valve, taken from engine No. 6,072 during its second overhaul.

The piston and big-end had run 903 hours.

The piston has been sand-blasted to ascertain if there were any cracks.

As regards light aeroplane engines, by far the greatest amount of experience exists on the "Cirrus."

TABLE VII.

SERVICE DATA ON JUPITER VI. ENGINES.

COLLECTED DATA FROM TWENTY OVERHAULS ON STANDARD DIRECT-DRIVE ENGINES.

AVERAGE TIME BETWEEN OVERHAULS, 336 HOURS.

Component.	Number off per Engine.	Number of Replacements.	Average Life Hours.	Max. Observed Hours to Date.	Average Cause of Replacements.
Crankcase	1	Nil	1162	1413	
Crankshaft	1	Nil	1162	1413	
Valve inlet	18	11	1091	1413	Worn on stem or defective seat.
Valve exhaust	18	59	683	1015	Worn on stem or pitted seat.
Valve spring	72	132	839	1413	Lost pressures.
Valve guide inlet	18	8	1060	1413	Scored and worn.
Valve guide exhaust	18	36	872	1279	Scored and worn.
Piston	9	6	813	1413	Gudgeon pin bosses oversize.
Piston ring	18	164	305	681	Oversize gaps.
Scraper ring	9	88	285	904	Oversize gaps.
Cylinder	9	2	960	1413	Scored barrels.
Cylinder head	9	Nil	1162	1413	
Big end bearing	1	2	872	1413	White metal collapsed.
Artic rod bearing	8	2	1116	1413	Wear.
Master rod	1	1	996	1413	Cracked.
Artic rod	8	Nil	1162	1413	
Gudgeon pin	9	36	697	1015	Worn in centre.
Artic rod pin	8	Nil	1162	1413	
Prop hub	1	Nil	1162	1413	

FIG. 18.
Components from Jupiter VI. engine, No. J.6072, after 903 hours' running in Imperial Airways Hampstead machine.

I have been able to obtain the following information through the courtesy of Colonel Darby, of the A.D.C. Company, and the Bristol and Wessex Aeroplane Club:—

TABLE VIII.

SERVICE DATA ON "CIRRUS" ENGINES.

DATA FROM THE BRISTOL AND WESSEX AEROPLANE CLUB.

Number of machines operated	3	
Type of machines operated	Moth	
Number of engines operated	5	
Period covered	18	Months
Total hours operation	1450	
Average hours operation per engine	290	
Maximum recorded hours on one engine	403	
Average hours between top overhaul	120	
Average hours between complete overhaul	360	
Man hours for top overhaul	25	
Man hours for complete overhaul	100	
Cost per running hour for overhaul and spares	1.1	Shillings
Average operating r.p.m.	1800	
Average fuel consumption, galls. per hour	4	
Average oil consumption, pints per hour	0.5	

TABLE IX.

SERVICE DATA ON "CIRRUS" ENGINES.

DATA FROM THE A.D.C. CO. FROM THREE AERO CLUBS.

Number of machines operated	4	
Type	School Moths & Avians	
Number of engines operated	4	
Period covered	$2\frac{1}{2}$	Years
Total hours running	3083	
Average hours per engine	771	
Maximum recorded hours one engine	820	
Average hours between overhauls	280	
Maximum hours recorded between overhauls	354	
Average man hours for overhaul	110	
Average hours life of parts requiring replacement, piston rings, rocker bushes, rear roller races	300	
Cylinder barrels	600	
Average operating r.p.m.	1780	
Average fuel consumption, galls. per hour	4·5	
Average oil consumption, pints per hour	1	

I am afraid the above rather scattered information is all the available data that I have been able to collect on the actual running times of air-cooled engines and their components.

In a previous paper I have endeavoured to outline the advantages to be obtained in the saving of man hours when overhauling radial engines, and those reasons dealing with air-cooled cylinders equally apply to the in-line air-cooled engine.

I believe I am correct in stating that these arguments have been borne out in practice during the last few years by air transport companies using air-cooled radial engines, and that a considerable saving in operating costs has been obtained therefrom.

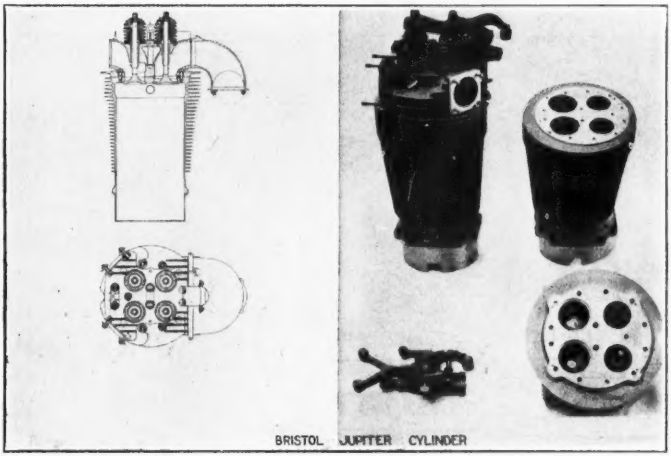


FIG. 19.

Bristol Jupiter vertical four-valve cylinder, closed steel barrel type.

I understand that an important saving has been made in the life of such components as cylinders and valves when using air-cooled engines. The cooling of air-cooled engines does not deteriorate with age as with water-cooled engines; also it is much easier to clean the outside of an air-cooled engine than to remove non-conducting scale from inside a water jacket.

I understand also, from Imperial Airways, that decarbonising has been less with air-cooled engines, and that " Jaguar " engines have run 1,600 hours without cylinder scraping.

On a basis of horse-power the original cost of large air-cooled radial engines should be lower than corresponding water-cooled engines, which consideration, combined with the fact that to the latter must be added the cost of the radiator system, favourably affects the total cost of the air-cooled power unit.

Sufficient experience has not yet been gained as to the cost of production of in-line engines of considerable power, but it is safe to say that these engines, if they come into general use, will not have such an attractive price saving as the air-cooled radial, although I think they should cost slightly less than the corresponding water-cooled unit.

The advantages of the air-cooled motor in extremes of climate, also dealt with in detail in my previous paper, are perhaps too hackneyed to more than mention in passing.

These claims have, I think, been fully borne out with radial air-cooled engines from actual experience during the last few years; also the considerable advantages of the very short warming up period necessary for air-cooled radial engines, a factor of vital importance to ships' fighters, night fighters, etc.

III. Constructional Details of Existing Air-Cooled Engines

At this point in the review of air-cooled engines in service it will be useful to examine some of the main components of various types of air-cooled engines, so as to obtain an idea of the service given by these parts and the possible development for the future.

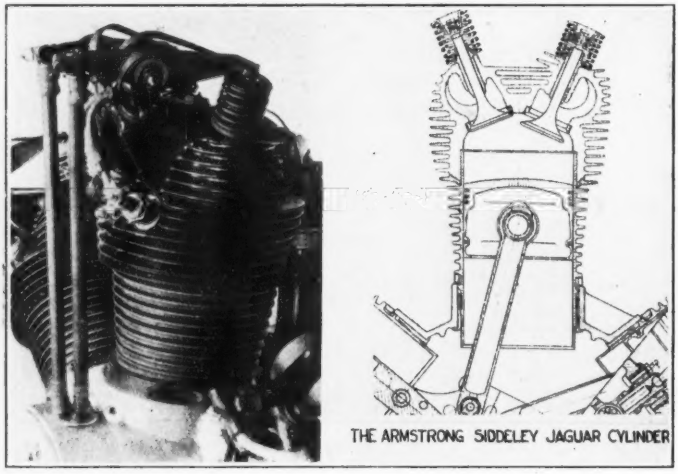


Fig. 20.

Armstrong Siddeley two-valve cylinder, open-ended type.

(a) Cylinder Construction

On all large types of air-cooled engines, where weight is a serious consideration, the cylinder barrels are made of medium carbon steel, the fins being formed integral with the barrel.

The forms of cylinder head construction fall under two main types, either a closed-ended cylinder barrel, with steel head formed integral with the barrel and an aluminium casting bolted to the head, carrying the valves and ports, as in the case of the "Jupiter" engine, or a cylinder barrel of the open-ended type, with an aluminium head carrying the ports and valve seatings, the head being open to the explosion of the charge and either screwed or bolted to the barrel.

The screwed construction, with locking ring, was first employed on the "Jaguar" engine, and has since been used on most of the American air-cooled radial engines, in some cases with a grip band to replace the Armstrong-Siddeley type of locking ring, or with a plain ground portion and no locating band of any sort.

From a theoretical point of view, I think the open-ended liner is probably the best design as it is more likely to give an even heat flow throughout the cylinder.

The Bristol Company, however, have up to the present time adhered to the closed steel barrel for their large four-valve cylinder of three litres capacity, as being a safer proposition and permitting the head to be re-serviced after extended periods of running.

With smaller bore cylinders, where only two valves are necessary, an aluminium casting, even with the reduced strength due to temperature, has proved quite satisfactory, but for the aluminium head of the large bore cylinder I am of the opinion that a "Y" alloy drop forging should be employed, as with four valves per cylinder the strength of the head is very seriously reduced, and castings are not altogether above suspicion for this purpose.

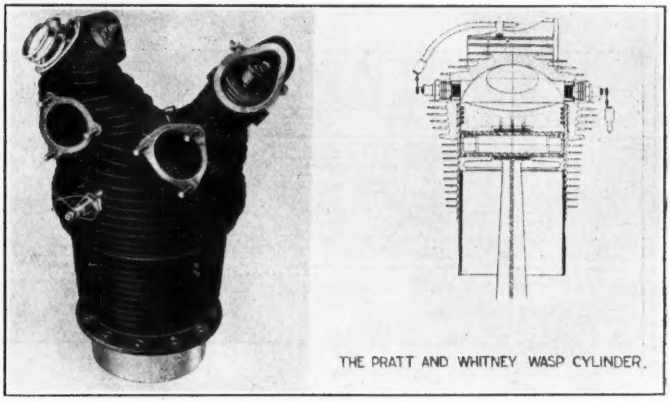


FIG. 21.

Pratt and Whitney Wasp two-valve cylinder, open-ended type.

Up to the present time, with the exception of the Curtiss "Chieftain," I know of no tested air-cooled aero engine which uses an overhead camshaft, and practically all air-cooled radial engines and in-line engines use push rod gear for the valve operation.

The development of overhead rocker gear for air-cooled engines is an interesting design problem upon which it is really necessary to spend a good deal of time in order to realise its difficulties. The more efficient the lay out of the valve gear the worse the drag, and if sufficient bearing surface is given to the rocker gear assembly to ensure really long life, the components require careful design or they will become bulky and heavy.

The Bristol "Jupiter" engine is, I think, the only type of radial engine in which any serious attempt has been made to compensate for the increased valve clearances when the cylinder is hot, and this is really a serious trouble on large cylinders of $5\frac{1}{2}$in. bore and upwards, as, without some form of compensation, the valve clearances become abnormal, which tends to rapid wear and probable valve spring breakage.

A very close similarity follows nearly all the two-valve open-ended American designs of cylinder head construction, and a number of them, such as the Pratt

and Whitney, have completely enclosed push rod gear. Complete enclosure certainly looks attractive, but without forced lubrication, which at present seems impracticable, it may provide a condenser for exhaust products, lead to corrosion, or possibly seizing up of valve guides.

With the completely enclosed gear it is undoubtedly a good deal more difficult to examine valves, valve springs, and rocker clearances, with any degree of accessibility; also the valve springs are apt to be a more difficult problem from a cooling point of view.

Ball bearings are undoubtedly a considerable advantage for the rocker fulcrum gear, although slightly heavier.

The protection of the cylinder barrel from corrosion is absolutely necessary; some form of zinc protection, or cadmium plating, is, in my opinion, essential.

The protection of the non-ferrous cylinder head is a good deal more difficult problem; enamel is used at the present time, but it is not altogether satisfactory.

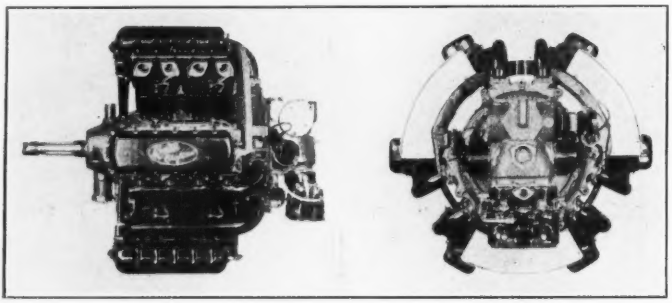


FIG. 22.

Curtiss Chieftain 12-Cylinder Hexagon.
5⅜in. bore, 5½in. stroke, 26.9 litres capacity,
600 b.h.p. at 2,200 r.p.m., 1.5lbs. per b.h.p.

Undoubtedly the " business end " of the air-cooled cylinder is one of the components calling for the greatest care in design, in order to obtain good thermal efficiency, combined with low drag and long life for the working parts, and, as is usual in so many engineering problems, a compromise has been the result.

So long as poppet valves are employed for the admission and discharge of the gases, I am of the opinion that the valve springs are better not entirely enclosed, providing steps are taken to protect the valve guides from dirt and water, which is quite feasible.

The rocker gear should be as rigid as possible, and I believe there is considerable scope in all existing designs for improvement in this respect.

The bolted-on open-ended cylinder head is not a feasible proposition for large bore cylinders, as the weight becomes excessive if sufficient bolts are used to prevent gas leakage, and expansion problems are very difficult to overcome.

" Y " alloy metal is very much better than aluminium alloys for a cylinder head construction, and for large cylinders I feel sure that the " Y " alloy drop forging is the real solution to the problem, and, properly tooled, the expense of this component is not serious.

Fig. 23, shown through the courtesy of the D.T.D., Air Ministry, gives details of the Bristol " Mercury " forged pent-house cylinder heads in different stages of construction.

The development of valve material in recent years has resulted in the production of alloy steels, such as cobalt chrome, and the high chromium ranges, which give excellent service as regards the head of the valve in an air-cooled engine.

Some of these steels are not too good on the valve guide, and there is an opening for a type of material which is equally good to that already named, from a corrosion point of view, on the head, and which will at the same time form a better bearing surface in the valve guide.

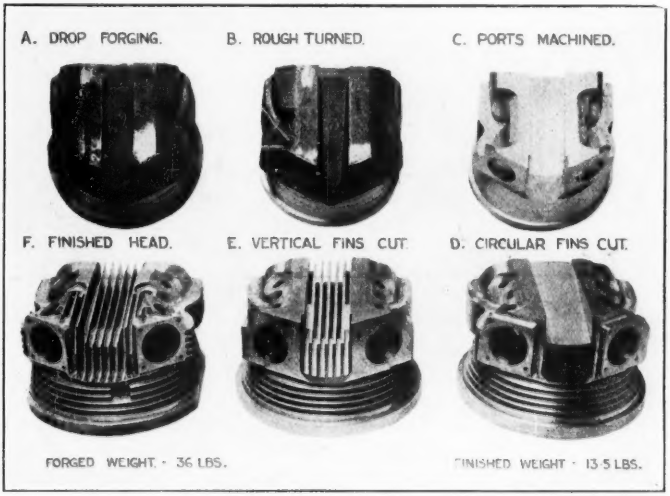


FIG. 23.
Bristol Mercury Y metal forged cylinder heads, showing different machining stages.

I am of the opinion that the enclosed overhead camshaft gear for in-line engines is worth exploring, although up to the present very little attention has been given to this type of gear, and it is apt to be heavy and expensive, unless the design work is very carefully carried out. With the overhead camshaft it is possible to get a good transference of the valve gear loading to the cylinder head, and thence to the crankcase, and although there is a general opinion that the overhead camshaft on an in-line engine would cause bending of the camshaft and its housing, due to varying cylinder expansion, I am doubtful if this would be a problem.

(*b*) *Pistons*

On early air-cooled engines, pistons were a source of considerable trouble, due to burning and seizing, but in most cases this has been traced to poor cooling, or unsound castings.

The technique of piston casting has been very considerably developed of late years, and I think we must give the American people due credit for leading

the way in " Y " alloy for use in pistons, which material is undoubtedly stronger and harder under the temperature running conditions of an air-cooled engine piston of, say, 400 to 420°C.

The radial engine does not permit of a very long skirted piston, and the weight naturally requires more careful consideration than in an in-line engine, owing to its greater effect on the big end loading.

There seems to be no " royal road " to air-cooled engine piston design, but, at any rate in the larger sizes, the best advice I can give for the development of a piston is by extended single-cylinder running. As a whole, on developed air-cooled engines, pistons give very little trouble, and a life of 1,000 hours is quite normal.

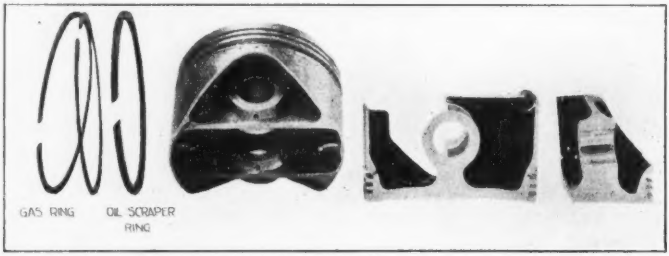


FIG. 24.

Jupiter piston, with gas and oil scraper rings.

Fig. 24 shows a view and section of the " Jupiter " engine piston, which is a " Y " alloy casting, and weighs 3.26 lbs., together with piston and scraper rings.

The oil scraping on an air-cooled engine in early days was somewhat of a problem, especially with the radial type engine, but a ring such as the type shown in Fig. 24, used on the Bristol " Jupiter " engine, is quite capable of dealing with the oil in all cylinders. This type ring is now extensively used on various types of engines.

For piston design, " Y " alloy forgings are certainly the right line to develop, and I am strongly in favour of a forging as against a casting for high duty supercharged engines, but on large bore cylinders a reasonably easy machining proposition is somewhat difficult, and it would appear that for all ordinary purposes a well-designed " Y " alloy casting is a better proposition than the forged piston, in which the heat flow has been curtailed in order to obtain easy machining.

(c) *Connecting Rod Assembly*

I think I am right in saying that all high-power radial engines use alloy steel master and auxiliary rods, machined all over, although I am of the opinion that for a small production radial, forged duralumin articulated rods would be a feasible proposition.

The use of master rod construction is practically universal on radial engines.

I believe that the floating big end bush, with built-up shaft, gives the longest life for the big end bearing, although its construction is somewhat of a problem for anything but the single-row radial.

Fig. 25 shows details of the "Jupiter" master rod, articulated rod, and floating big end bearing. The white metal is centrifugally cast, and is as thin a coating as is feasible. With the floating bush big end construction a hardened bush can be used in the master rod, which gives a very long life without replacement.

Floating bushes for articulated rod pins and gudgeon pin bushes are, I consider, the best practice, and give very little cause for complaint.

The case-hardening of a large crankshaft to obtain a really hard bearing surface on the crankpin has been carried out on certain experimental engines, but is not a production proposition, and the introduction of reliable crankshaft stampings, the pins of which might be treated by the nitriding or nitrogen hardening process, is an obvious line of development, and would be of great value to the air-cooled engine constructor.

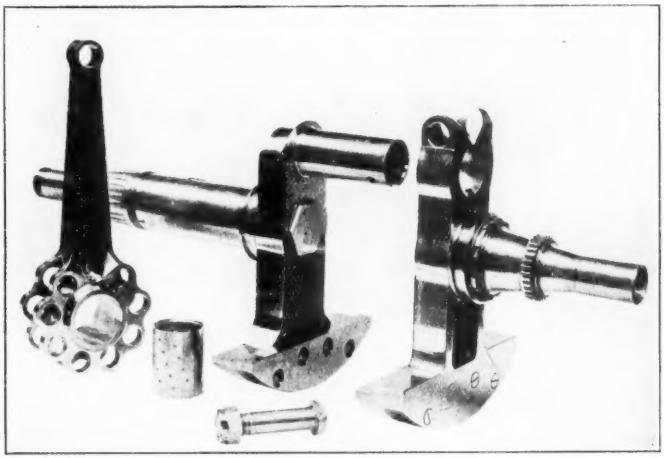


FIG. 25.

Bristol Jupiter big-end assembly components, showing crank pin, master rod and big-end floating bush.

The problem of crankshaft and connecting rod design for the in-line type engine may be fairly stated to be on "all fours" with the water-cooled engine, except that as the space between the cylinder bores must be at least $33\frac{1}{3}$ per cent. of the bore of the cylinder, it may be expected that for a given size of engine the air-cooled crankshaft will be longer than the water-cooled crankshaft, and therefore more liable to give rise to torsional vibration problems.

For the small type of in-line engine, the duralumin drop forged connecting rod, on similar lines to automobile practice, would appear to be an excellent solution, and I understand that this type of rod is used with good results on the "Cirrus" engine.

(*d*) *Crankcases*

Although the radial engine crankcase is, as compared with the in-line water-cooled crankcase, a comparatively simple foundry proposition, I am strongly in favour of a duralumin drop forging for this purpose.

Since the Bristol Company introduced drop forgings for the crankcase on their " Jupiter " engines, failures have been unknown.

Fig. 26 shows two views of the front and back halves of the " Jupiter " forged crankcase in the rough and finished state. The profiling operations on this crankcase are carried out with semi-skilled labour, with hardened formers, and the crankcase is a really satisfactory production job.

This problem would appear to be more difficult on multi-row radials, although if it could be incorporated as a satisfactory production job, it would appear to be very well worth while.

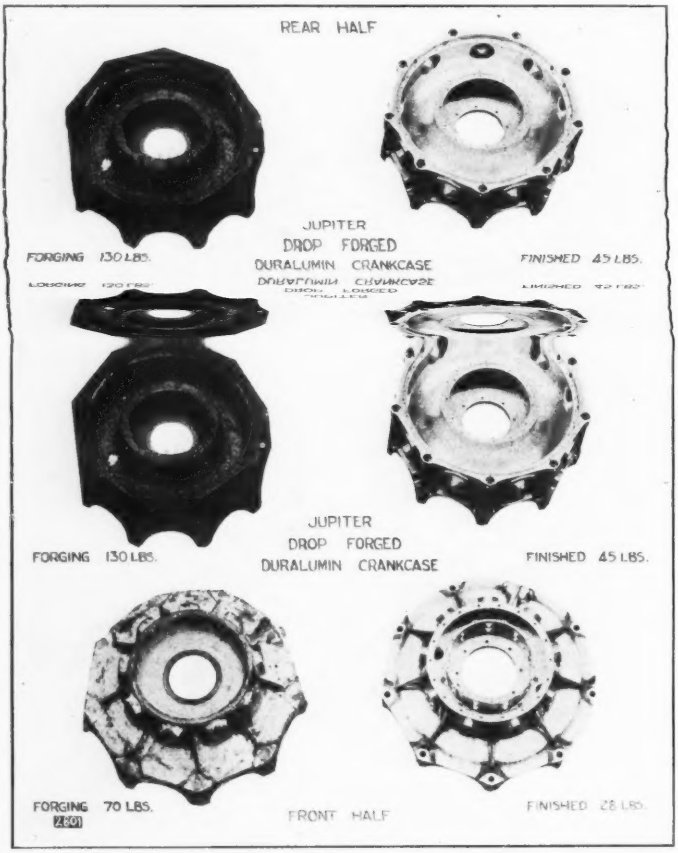


FIG. 26.

Bristol Jupiter forged duralumin crankcase, showing forged and finished components.

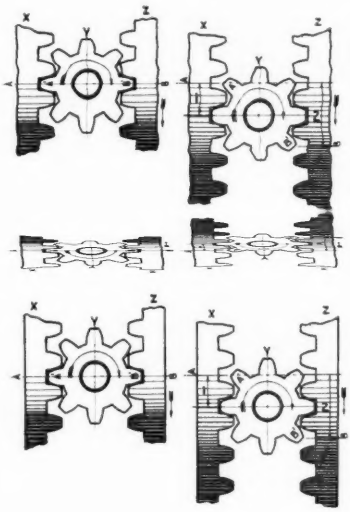
The problems of crankcase construction for the in-line air-cooled engine designer are, if anything, more difficult than those on corresponding water-cooled engines.

The production of a satisfactory in-line crankcase casting is no easy problem, and the fact that with the air-cooled engine, due to conduction, the average temperature of the crankcase will be higher than with a water-cooled engine, is a fairly sure indication that the scantlings of the air-cooled engine crankcase will have to be greater than with the water-cooled engine, as the material would be hotter and not so able to deal with stress reversals.

I do not know if it is possible to expect, in the near future, crankcases cast in a permanent mould, or whether it is even within the bounds of possibility to produce a forged aluminium case for in-line engines, but I do expect that if we are going to see large air-cooled engines in the future, the solving of the crankcase problem will be no mean one.

(e) *Reduction Gearing for Air-Cooled Engines*

Although several aircraft constructors have for some years complained of the propeller speeds of the larger air-cooled engines, it is only recently that air-cooled engines have been fitted with reduction gears, and although the cooling problem is increased by the introduction of gearing, consequent upon the slower running larger-bossed propeller, the increase in the performance of the aircraft has been most marked.



X Fixed or stationary bevel.
Y Pinion mounted on propeller shaft arm and free to revolve around its own axis and in mesh with **X** and **Z**.
Z Driving bevel mounted on and revolving with crankshaft.

OPERATION.

(1) The crankshaft drives Z at engine speed in direction of arrow.
(2) **Z** can only move by rotating **Y**.
(3) For **Y** to rotate **Z** must move relative to **X** or vice-versa. If both **X** and **Z** were free to move, clockwise rotation of **Y** one tooth would result in **X** moving backward one tooth and **Z** moving forward one tooth, therefore there would be a relative movement of two teeth between **X** and **Z** for each one tooth movement of **Y**.
(4) As **X** is fixed or stationary, **Y** can only rotate by running along **X**, therefore while **Y** moves forward

(1) The crankshaft drives Z at engine speed in direction of arrow.
(2) **Z** can only move by rotating **Y**.
(3) For **Y** to rotate **Z** must move relative to **X** or vice-versa. If both **X** and **Z** were free to move, clockwise rotation of **Y** one tooth would result in **X** moving backward one tooth and **Z** moving forward one tooth, therefore there would be a relative movement of two teeth between **X** and **Z** for each one tooth movement of **Y**.
(4) As **X** is fixed or stationary, **Y** can only rotate by running along **X**, therefore while **Y** moves forward one tooth, **Z** must move two teeth forward relative to **X**.
(5) As **Z** has an equal number of teeth to **X**, **Z** will complete two revolutions while **Y** rotates around **X** once, thus giving a 2 : 1 reduction between **Z** and **Y**, or between engine and propeller shaft.

Note.—The above results are independent of the number of teeth in pinion **Y**.

Farman Jupiter Reduction Gear Diagram, showing relative movement of Crankshaft and Propeller Shaft.

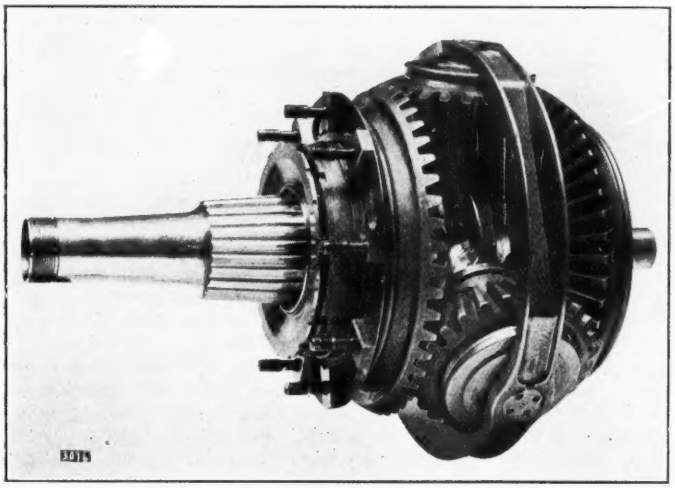


FIG. 27.

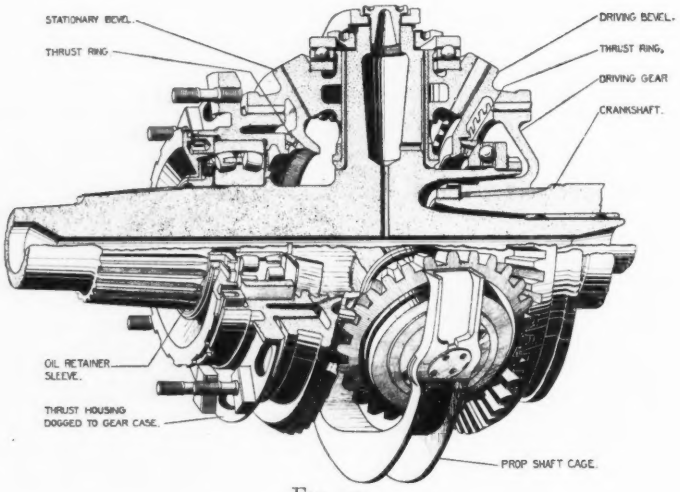


FIG. 27.
Farman Jupiter reduction gear.

Fig. 27 shows a view and explanatory diagram of the Farman type bevel reduction gear employed on the "Jupiter" with .5 reduction, and Fig. 28 shows a view and diagram of the Lorraine type epicyclic reduction gear employed on the Armstrong-Siddeley "Jaguar" with .66 reduction.

The reduction gear fits very neatly on the radial engine and has certainly increased its performance very much indeed.

With the "Jupiter" geared engine the increase in performance on certain aircraft, as compared with the ungeared engine, has been of the following order, viz.:—

Two-Seater General Purpose Machine of approximately 4,400 *lbs. All Up Weight.*

Climb time to 15,000 feet reduced 23 per cent.
Speed at 15,000 feet improved 11 to 12 per cent.

Single-Engined Air Liner of approximately 8,000 *lbs. All Up Weight.*

Ground rate of climb improved 47 per cent.
Ground speed improved 9 to 10 per cent.

Twin-Engined Bombing Machine of approximately 13,000 *lbs. All Up Weight.*

Climb time to 10,000 feet reduced 47 per cent.
Speed at 10,000 feet improved 10 to 11 per cent.

It is realised that both these reduction gears have only recently been introduced, but I am of the opinion that reduction gears will be used to a much greater extent in the future, and that the design of the radial engine crankshaft is particularly suited for a reduction gear, and is not prone to many of the problems of inertia torque which are sometimes introduced with a reduction gear on an in-line engine, and that the main harmonic can be kept well below the running speed of the engine.

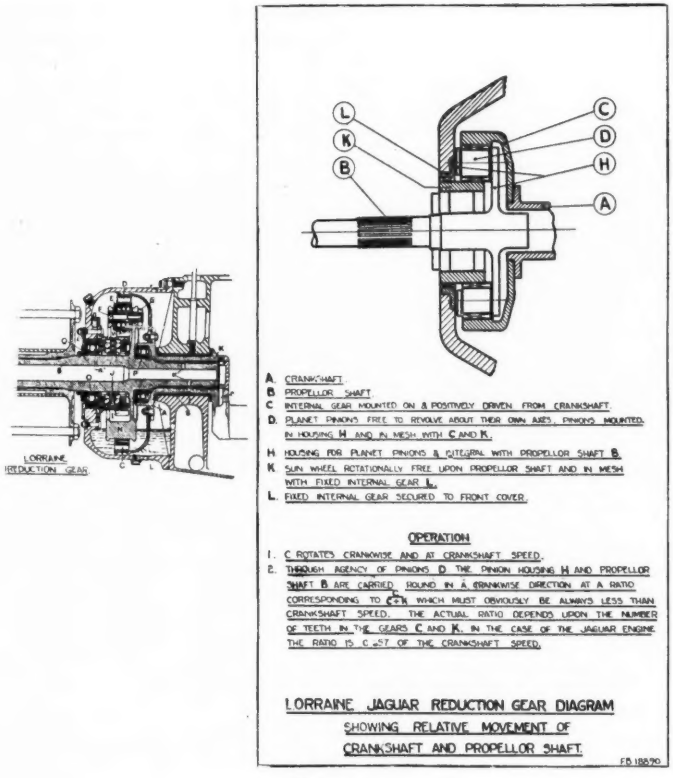

LORRAINE
REDUCTION GEAR
L
K
B
C
D
H
A
A. CRANKSHAFT.
B. PROPELLOR SHAFT.
C. INTERNAL GEAR MOUNTED ON & POSITIVELY DRIVEN FROM CRANKSHAFT.
D. PLANET PINIONS FREE TO REVOLVE ABOUT THEIR OWN AXES. PINIONS MOUNTED IN HOUSING H AND IN MESH WITH C AND K.
H. HOUSING FOR PLANET PINIONS & OUTGRAL WITH PROPELLOR SHAFT B.
K. SUN WHEEL ROTATIONALLY FREE UPON PROPELLOR SHAFT AND IN MESH WITH FIXED INTERNAL GEAR L.
L. FIXED INTERNAL GEAR SECURED TO FRONT COVER.
OPERATION
1. C ROTATES CRANKWISE AND AT CRANKSHAFT SPEED.
2. THROUGH AGENCY OF PINIONS D THE PINION HOUSING H AND PROPELLOR SHAFT B ARE CARRIED ROUND IN A CRANKWISE DIRECTION AT A RATIO CORRESPONDING TO $\frac{C+K}{K}$ WHICH MUST OBVIOUSLY BE ALWAYS LESS THAN CRANKSHAFT SPEED. THE ACTUAL RATIO DEPENDS UPON THE NUMBER OF TEETH IN THE GEARS C AND K. IN THE CASE OF THE JAGUAR ENGINE THE RATIO IS C.=57 OF THE CRANKSHAFT SPEED.
LORRAINE JAGUAR REDUCTION GEAR DIAGRAM
SHOWING RELATIVE MOVEMENT OF
CRANKSHAFT AND PROPELLOR SHAFT.
FD 18870

FIG. 28.
Lorraine Jaguar reduction gear.

At present it is perhaps early to speak of the actual service of these gears, but I know of absolutely no failure of the gearing on these engines, and we have experience in England of a "Jupiter" engine running with a reduction gear in service for 360 hours, and the gearing is in perfect condition; and a Farman gear on a "Jupiter" engine on the Continent has been run for over 800 hours without replacement of any of the reduction gear parts.

As regards the gearing of in-line air-cooled engines, of which no experience has been obtained at present, it would appear that the dynamic problems are generally similar to the water-cooled engine. The use of a reduction gear on four or even six-cylinder engines, without a flywheel, is a difficult problem for solution, although it was noted at the recent German Exhibition there were certain large six-cylinder in-line water-cooled engines shown in which a reduction gear was fitted.

With an in-line air-cooled engine, if the gearing is not kept on the central axis of the crankshaft it would appear that the cooling of the cylinder heads would be a very serious problem. On the other hand, with an inverted air-cooled engine, an out-of-line gear would give a satisfactory thrust line for the propeller, and at the same time would help the cooling of the cylinder heads.

(f) *Arrangement of Auxiliary Components*

Generally speaking, I think it may be stated that the arrangement of components and the reliability of these parts on air-cooled radial engines is at least as satisfactory as in a water-cooled engine, and give excellent service, quite apart from the obvious remark that in all types of air-cooled engines one can eliminate the water pump and drive and all water jacket connections.

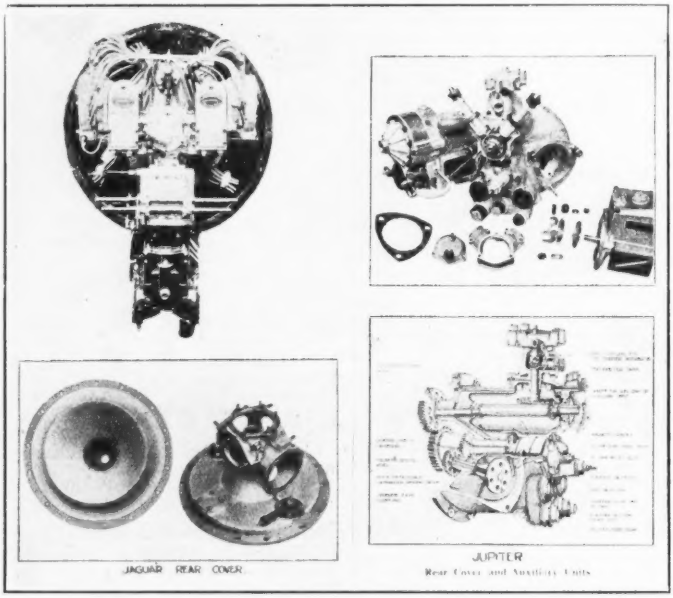


FIG. 29.

Jupiter and Jaguar rear covers, showing grouping of accessories.

Fig. 29 gives the back view of the "Jupiter" and "Jaguar" covers, showing the various components such as magnetos, carburettors, oil pump, etc.

I am not in favour of mounting the magnetos on the nose of an air-cooled radial engine, as has been done on certain American engines, as it undoubtedly affects the cooling and the magnetos would appear to be in a more vulnerable position.

Flange-mounted magnetos mounted at an angle, or possibly still better at right angles, to the crankshaft axis, provide the most accessible arrangement.

For commercial engines a telemeter drive and electric generator drive are very desirable; the latter permits the introduction of a generator, which may be enclosed in the fuselage.

The problems and lay-out of the components and their drives for the in-line air-cooled engine are very similar to the water-cooled engine.

Accessible oil strainers, oil centrifugers, flexible oil pipe connections, and oil thermometer bulb connections should be supplied by the engine makers in the most suitable form and as standard equipment.

With the introduction of high compression and supercharged engines, an automatic control, to obviate abuse of the engine at low altitudes, should be standardised and built into the engine.

Summarising, therefore, the constituent parts of air-cooled engines as they exist to-day, I would submit that the following will make for greater reliability and longer service, viz. :—

1. The introduction of non-ferrous drop forgings, wherever possible, on all such components as crankcases, cylinder heads, pistons, nose-pieces, etc., and the encouragement of drop forging technique to give us, wherever possible, forgings for all components which at present are castings, except on such parts as carburettors, induction elbows, etc.
2. The further development of overhead valve gear to reduce drag and prolong life of the components.
3. The development of valve, valve guide and valve stem materials, which will give longer life under the working conditions of air-cooled engines, where the whole mechanism is not enclosed in a pressure fed system.
4. The better protection of cylinder heads against corrosion.
5. The use of floating bushes, wherever possible, in the connecting rod assembly, and the introduction of a material for crankshafts and connecting rods which can be hardened locally by such a process as nitrogen hardening, without introducing the complication and difficulties of case hardening.

   Chromium plating is an alternative to such a scheme and development is proceeding along these lines, but there is a vast gulf between the chromium plating of a household article and a highly stressed part such as a connecting rod bore or crankpin, and one is always suspicious of a coating of any sort which may flake off.

IV. Air-Cooled Engine Installation

The question of air-cooled engine installation is a subject covering a wide field which I cannot attempt to deal with in detail in this paper, but there are certain broad principles affecting air-cooled engines in service to which I wish to refer, which are as follows :—

(a) Cooling Capacity

In Mr. Penn's paper, entitled "Aeroplane Engines in Flight," which he read before this Society last November, he gave us some interesting data in respect of the experimental work carried out at the R.A.E., to determine the cooling capacity and radiator efficiency on water-cooled engine installations. Up to the present time no such basis has been laid down for air-cooled engines.

From a theoretical point of view, in order to obtain maximum efficiency from the engine, and minimum drag, each air-cooled engine should have a different fin capacity, according to the type of aircraft into which it is installed. This, of course, is impracticable from a manufacturing point of view, but it is submitted that to get the best service out of air-cooled engines, some definite schedule should be laid down for measuring the temperatures, both of the cylinders and crankcase, in a new installation, and if this were systematically carried out the service obtained from air-cooled engines in certain installations could be improved.

This lack of attention to temperatures on air-cooled engines is probably due to the fact that in the past the air-cooled engine has had a very large cooling capacity, but now that these engines are being supercharged and geared, and

compression ratios increased, the necessity for carrying out these tests, before passing a machine into production, is of considerable importance.

In the past it has been common practice to instal the same type of air-cooled engine in several different aircraft.

In one machine the engine is installed with the cylinders well exposed to the slipstream, with a reasonable air speed over the cylinder barrels, and no projections behind the cylinders to interfere with the free get-away of the cooling air.

In the next machine this same engine has to function in front of a very large body, where the air speed over the cylinder barrels may be 30 per cent. less, and what is even worse still, the engine may be mounted eccentric to the body behind it, with the result that some cylinders are much better cooled than others.

Again, there may be something in the installation which causes a projection locally behind one of the cylinders, which may raise the temperature of that individual cylinder.

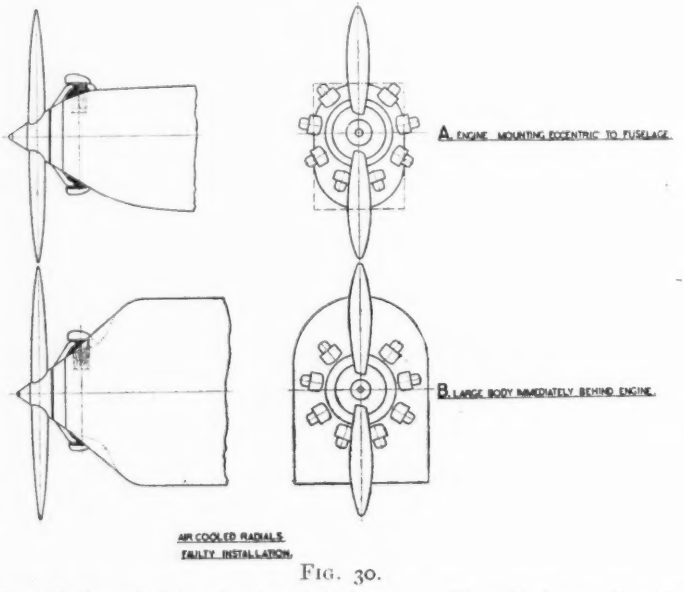

A. ENGINE MOUNTING ECCENTRIC TO FUSELAGE
B. LARGE BODY IMMEDIATELY BEHIND ENGINE.
AIR COOLED RADIALS
FAULTY INSTALLATION.

FIG. 30.

Installation sketch, showing interference with cylinder cooling by local projections.

Fig. 30 illustrates the meaning of the above remarks.

The question of speed very naturally affects the cooling capacity of any air-cooled engine, and it is common practice for the same type of engine to be installed in different machines, the cruising speeds of whch vary over a wide range.

The above remarks will seem obvious to most of you, and probably the engine maker has been as much at fault as anyone in not tackling this matter more systematically, and developing practical and rapid methods for determining the suitability of the cooling on each individual installation.

The Bristol Company are at the present moment endeavouring to remedy this defect by supplying to their customers a simple equipment, with which it should be possible in a short period to determine whether the engine is being properly cooled or not.

I believe that this problem has in the past been masked on air-cooled engines, because on the water-cooled engine, if the cooling capacity is insufficient, trouble is experienced at once.

In the case of the air-cooled installation, however, the engine is more patient and does not so quickly and so violently object to the way it has been installed; the adverse symptoms are not always immediate, and the engine may run for quite a long period before the inadequate cooling makes itself felt, in the form of gummed rings on some individual cylinder, or some other defect.

(*b*) *Crankcase Cooling and Lubrication*

It is not always fully realised the effect of crankcase cooling on the service obtainable on an air-cooled engine. On the radial air-cooled engine the capacity of the crankcase is comparatively small, and the crankcase has to deal with a certain proportion of the cooling by convection, the amount depending on whether the cylinder heads are well cooled or badly cooled.

It is quite common for the crankcase temperature of an air-cooled engine to vary as much as 50 per cent. on the same type of engine in different installations, and the effect of such a difference in temperature is obvious on the satisfactory running of the engine, both from the point of view of actual working clearances, and on the temperature of the lubricating oil.

On general principles, the slower the machine and the poorer cooling to the cylinders, the greater need for adequate crankcase ventilation.

As at any rate a portion of the induction system is in most air-cooled engines contained in the crankcase, the temperature of the latter also affects the distribution and general running of the engine. Also, crankcase temperatures which may be satisfactory near the ground may not be so at high altitude.

Here again it is considered that the engine constructor should provide a more definite schedule as to the temperatures permissible, and that this matter should be closely investigated according to the type of machine.

Fairly recently there has come to my notice a case where four identical air-cooled engines were in competition in different aircraft. All four machines had, to the eye, a very similar type of cowling; three required oil coolers, and the fourth functioned absolutely satisfactorily without any oil cooler at all.

As the machines were built for the same competition, the difference in speed range was not sufficiently great to account for this discrepancy, and the machine in question had undoubtedly some cooling characteristics very different to the others.

On a triple-engined aircraft, where the centre engine is in front of a large body, and the temperature of the crankcase is high, as compared with the wing engines where the crankcases are thoroughly well ventilated, it has been noted that the wing engines will run 20 to 25 per cent. longer without requiring the pistons to be decarbonised as compared with the centre engine, clearly showing how attention to this point will prolong the life of the engine in service.

Fig. 31 will illustrate more clearly what is meant by the necessity for crankcase ventilation.

I have come across instances where insufficient attention to the points raised under the above two headings have caused engines to run below par, and where, if the installation had been left as it was, indifferent service might have been given by the engine, necessitating unnecessary repairs and renewals, with conse-

quent reflection on the air-cooled engine. By fairly simple modifications the temperatures have been reduced so that the engine has given excellent service.

These remarks apply to the radial type of engine, with which I am familiar, but I am quite convinced that similar remarks apply to the in-line air-cooled engine, and that if in the future we are going to see large air-cooled in-line engines functioning satisfactorily, reasonable care and intelligence will have to be used to develop a scheme by means of which the necessary velocity of air is passed through the fin cells of each individual cylinder with minimum disturbance and interference.

If these engines are to give satisfactory service in comparatively low-speed aircraft, carefully considered cowling must be used to direct the air round the cylinders, and it will certainly not be possible to instal the engine so that it is simply exposed to the slipstream.

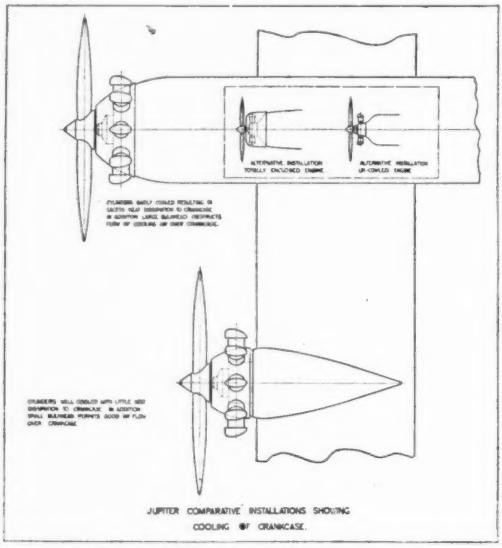


FIG. 31.

This problem I do not say is impossible, but when one sees the haphazard way in which some air-cooled radial engines have been installed in the past, it makes one realise what the designer of large in-line air-cooled engines has got to face.

(c) *Air Intake and Exhaust Outlet Systems*

The air intake and exhaust outlet systems on air-cooled engines, owing to the special characteristics of the air-cooled engine, require somewhat different treatment to the corresponding components on water-cooled engines, and their suitable arrangement very materially affects the service rendered by the engine as a whole.

All petrol engine carburettors require some form of heating, and the air-cooled engine is not able to draw upon the heating element obtainable from a water system fitted with shuttered control.

As I have hinted above, I feel sure that in the future we shall have variable and adjustable heating systems on air-cooled engines, but at present the only means of heating the carburettor and air intake is by the hot return oil from the engine, warm air from the cylinders, or hot spot from the exhaust gases.

Oil, owing to its low specific heat, is a poor medium for this purpose, although it is pretty generally used at the present time, and recourse has to be found in some installations to drawing warm air from the cylinders, or by leading exhaust gases to some point in the induction system near to the carburettor.

The problem is not as easy as it looks, because here again the question of different installations, different cylinder and crankcase temperatures, and the divided responsibility of the aircraft constructor and the engine builder make for a number of "unknowns," which require solving on individual installations.

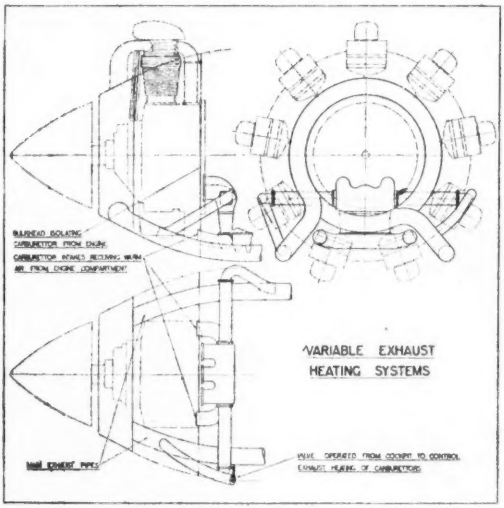


FIG. 32.

There is also the question of fire prevention in the event of a crash which requires careful consideration.

There is also the problem of dealing with the air intake in the case of seaplanes, and machines operating abroad, where water, sand or dirt may be sucked into the air intake, from the effect of the propeller or floats, when the machine is at rest or taking off.

I have found in some instances that distribution, and consequently the service obtained from an engine, has been upset owing to incorrect fitting of air intakes, leaving out altogether the question of the variation in smooth running obtained with two identical engines in different aircraft, which I believe in many instances may be attributed to the arrangement of the air intake.

What is wanted is some system which does not require individual attention on each installation, and eliminates the rather haphazard "cut and try" method which is so often in operation, and I suggest that the solution of the matter is some definite flame damping device in the induction system, which will enable the air intake to be placed with safety inside the cowling; that this air intake should be provided with some simple form of air cleaner, and that the induction

system should be provided with exhaust heating, which can be definitely controlled from the pilot's cockpit.

Exhaust heating, in my opinion, is absolutely necessary for reliable running and good distribution in cold climates.

If the engine maker will face up to some such system as outlined above, this could be made universal for all types of aircraft, and would, I am quite sure, prolong the service obtained from air-cooled engines.

Fig. 32 shows the arrangement of such a scheme.

For comfort and night flying the exhaust gases on an air-cooled engine require dealing with adequately, and I believe that an air-cooled engine, with a properly designed collector system, gives better service than without, but if the system is of insufficient area the cylinder temperatures of the engine are naturally increased, with serious results to the engine generally, and indifferent service is certain to ensue.

The question of fire prevention also comes into this matter, and it is most important that the collector should be so arranged that it is not shielded from the slipstream on any surface and so has hot spots which would cause dangerous temperatures.

Fig. 33 shows the "Jupiter" VI. exhaust collector and also the collector for the new Wright "Whirlwind," with ventilating sleeve and neat adjustable cooling to the crankcase.

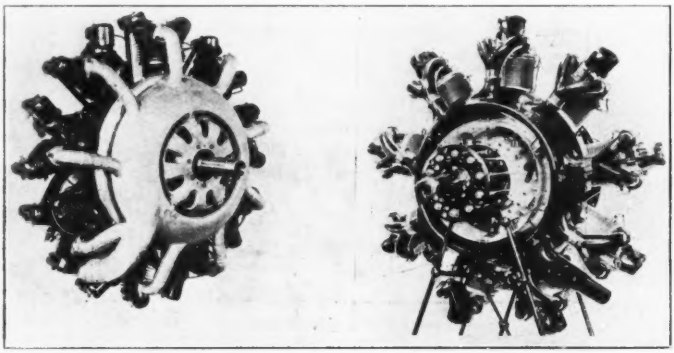


FIG. 33.

Bristol Jupiter and Wright Whirlwind exhaust collectors, showing adjustable cooling to crankcase.

(*d*) *Fuel and Oil*

As is the case on all petrol engines, the service rendered by them is affected by the use of suitable fuel and oil.

Two or three years ago we were informed that the makers of British air-cooled aero engines were far too faddy about the fuel and oil used on their engines, and that American air-cooled engines would run on ordinary grades of commercial motor car fuel and oil.

It is significant to note that at the Aeronautical Conference held at Chicago in December of last year, considerable attention was given to the question of fuel and oil for air-cooled engines on commercial service.

Some valuable data was given as the result of long experience with air-cooled engines on air transport, and it was very clearly brought out at these

discussions the value of using high grade fuel, and that the extra cost was more than paid for in the longer service obtained from the engine and the longer period between overhauls. The result of these discussions in America was to decide that definite standards should be laid down for fuels for air transport engines in America. Fortunately, in England, we are provided with excellent fuels and have little complaint in this respect, but engines going abroad are often expected to run on low grade fuels, for which they have never been designed.

If there is a lack of carburettor heating, referred to in a previous section, the effect on an engine is far more serious than if there is adequate heating and, in my opinion, this is a further claim for variable heating control to the carburettor system.

This question of poor fuels in out-of-the-way districts is a serious matter, and I believe the most practical solution is to use a dope.

I therefore think it behoves the engine builder to make quite sure that the material used in his valves, valve seats, valve guides, etc., is such that it will stand, without deleterious effects, a reasonable quantity of dope as, in my opinion, within the next two years the use of some such dope as ethyl fluid will be almost universal on aircraft engines, at any rate in undeveloped countries.

As a result of considerable experimental work and careful selection of materials, I have definitely proved that reasonable quantities of dope can be used without any bad effects on the wear and tear of the engine.

On the question of lubricating oils, I think there is a good deal more to be said for the American view.

Here again the best oil is the cheapest when considering operating cost and overhauls, but the most expensive oil will not necessarily give the best service.

Some troubles in service have been attributed to air-cooled engines employed in out-of-the-way districts using unsuitable oils.

In these countries the use of compounded oils is not always possible, and I am of the opinion that it is necessary for the air-cooled engine to be able to run satisfactorily on a high grade pure mineral oil.

Some considerable amount of experimental work has been carried out during the last few months in this country on air-cooled radial engines using pure mineral oil, and both the Armstrong-Siddeley Company and the Bristol Company have completed long tests on pure mineral oils with complete success, and I think that within a short time we shall see air-cooled radial engines in this country operating regularly with pure mineral oil.

I think it is desirable in air-cooled engines to use an oil of different viscosity for summer and winter use.

The use of mineral oil will certainly help the dope question as there is then less tendency for rust and deposit when using dope.

For the reasons explained in previous paragraphs, the mean average temperature of the oil from an air-cooled engine may be higher than with a water-cooled engine, and to prevent sludging it is considered that the introduction of a centrifuger as a standard part of an air-cooled engine installation is a highly desirable feature.

Some considerable work has been done in this respect, and I think we are in a position to ask aircraft constructors, as an inducement to use mineral oil, to instal, at any rate on all commercial aircraft, a proper oil cleaner. Such a cleaner will, I am convinced, considerably extend the service rendered by air-cooled engines.

V. The Possible Lay-out of Air-Cooled Engines

Most of the foregoing remarks in this paper apply directly to the air-cooled radial engine, because this is the type of engine with which I have been most closely associated, and air-cooled radial engines are undoubtedly used in larger numbers at the present time than are the in-line air-cooled engines.

During the last few months, however, a great deal of attention has been given generally, and in the Press, to the in-line air-cooled engine, and prophesies have been made that this type of engine is going to entirely displace the air-cooled radial. So much so is this the case that only a few months ago in this very room I was asked by an authority on aviation why it was that the Bristol Company were falling so far behind in the air-cooled engine world, in so much that they were not producing an in-line air-cooled engine.

Now I do not believe that the air-cooled radial engine is on the wane. It is impossible and undesirable for me to go at length into the reasons why I think this is so.

I have already endeavoured to outline, in a previous paper, my views as to the advantages of the air-cooled radial engine as regards light weight, production and repair facilities, use of symmetrical components, and comparatively easily obtained raw material, etc.

These very real and practical advantages have been proved on many different types of aircraft in all countries during the last few years, and are the main reasons why aerial transport companies are almost without exception demanding air-cooled radial engines on nearly all their new and projected types of commercial aircraft throughout the world.

In championing the air-cooled in-line engine, a meritorious effort is being made to reduce the drag of the air-cooled radial, and I hope that there will be several definite fields for the air-cooled in-line engine, apart from the smaller sizes already employed on light aircraft.

The 4-cylinder in-line "Cirrus" and "Gypsy" have already proved what can be done in this direction.

I am of the opinion, however, that with larger types of in-line air-cooled engines, which entail cylinder bores of five inches and upwards, the cooling problems will require considerable attention, and it will be very interesting to ascertain how much difference there will be between the large air-cooled radial and the corresponding in-line engine, provided they are both given the same chance as regards cowling, and the lead-in of the cooling air to their respective fin cells with the minimum drag and interference.

I feel that there is somewhat undue optimism in regard to the performance to be obtained from the large air-cooled in-line engine in this respect, and I am also convinced that there is much to be done by improving the lay-out and consequent drag of the air-cooled radial engine by suitable cowling.

As I have endeavoured to outline, apart from the cylinders, the air-cooled in-line designer is faced with exactly the same problems as on the corresponding layout of water-cooled engine, except that in certain instances his difficulties may be increased.

There is a considerable amount of experimental work proceeding at the present time along the line of reducing the drag of the air-cooled radial, which it would be premature to discuss in this paper, but if the aeroplane designer will give the radial engine maker as much consideration in cowling as the in-line engine maker will undoubtedly require, I think we shall see very interesting results.

As there has been so much talk of late as regards the most suitable types of air-cooled aero engines, I propose to conclude this paper by being sufficiently rash to consider some alternative lay-outs for various sizes of air-cooled engines most urgently needed for present requirements.

The types of engines I have dealt with are as follows, viz:—

1. The 80 to 100 h.p. engine.
2. The 200 to 250 h.p. engine.
3. The 350 to 450 h.p. engine.
4. The 500 to 600 h.p. engine.

In forming conclusions the following qualities have been considered:—

1. Regular firing order.
2. Transverse couples.
3. Longitudinal couples.
4. Largest unbalanced force.
5. Frontal area—actual and equivalent.
6. Heat units dissipated per unit surface.
7. Simplicity and manufacturing characteristics, which mean prime cost and maintenance.
8. Weight.

The above characteristics are plotted in the form of a graph shown in Fig. 34. I realise that such a graph is very ambitious and open to any amount of dissection and criticism, but I hope it may be possible to draw some constructive conclusions from it.

Headings Nos. 1, 2, 3 and 4 have been plotted as the result of an investigation of the balance and firing order of the different types under review. As

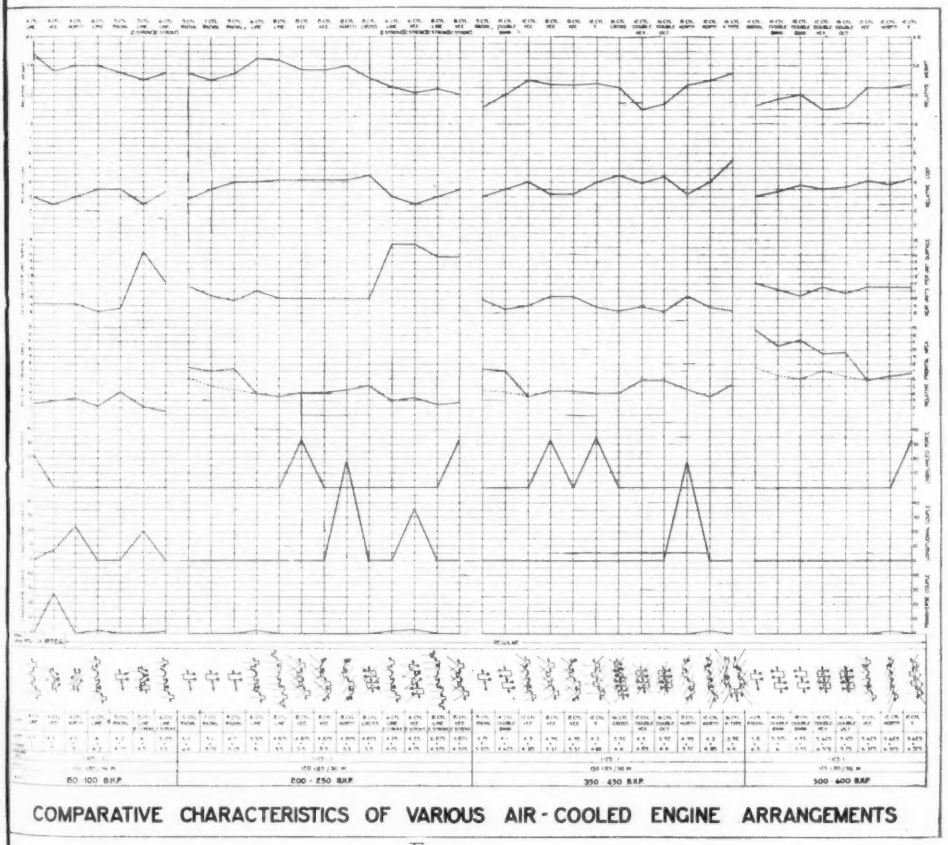


FIG. 34.

Air-cooled engine lay-outs, diagram showing comparative design characteristics.

far as possible freak lay-outs have been avoided, and such arrangements as 6, 9 and 18 cyl. λ engines, which have, I think, from time to time been suggested, are not included, as the balance or firing order becomes impossible.

As a general principle, the graph shows that one of the first considerations is the desirability of approaching as nearly as possible perfect balance.

In each category the number of cylinders has been kept as low as possible, commensurate with a reasonable torque curve.

Heading No. 5 has been obtained by taking an area enclosing the cylinders and cooling gear, plus the area of a circle enclosing the engine bearers.

Such a compilation is hard on the radial, in the light of the latest experiments on cowling, and complimentary to the larger in-line engine, for the reasons stated elsewhere in this paper, and alternative figures have been given which are considered to most nearly represent a fair comparison.

For heading No. 6 an allowance of 0.32 sq. ins. per b.h.p. has been made, equivalent to 20 cubic ft. required per b.h.p. at a speed of 100 miles per hour.

Heading No. 7 is certainly open to criticism and is purely empirical, as so much depends upon quantity, production, class of workmanship, etc.

It has been assumed that the first two categories are intended for the smaller classes of commercial aircraft, where price is of the utmost importance, whereas the third and fourth categories are intended for military and large commercial aircraft, where the highest class of workmanship is desirable.

An accurate figure for heading No. 8, without investigating the design details of each engine, is impossible, but the results are obtained from another graph not shown, in which the standard wt./h.p. was plotted against a considerable number of different engines already in existence, and where it has been assumed that an air-cooled engine of given type and size would weigh the same as the corresponding water-cooled engine dry.

If conclusions are permissible from such a heterogeneous collection of data, I would like to add the following comments on the four categories of engines

The 80 to 100 h.p. Light Plane Engine

In spite of the unbalanced forces in the 4-cylinder in-line engine, the fact that it has already given excellent service is an argument in favour of it being, most probably, the best compromise.

Reasonable balance, combined with low cost, are more important than specific weight in this category. Psychology also plays its part on this type, and the fact that the in-line engine more nearly approaches the motor car engine has, I believe, affected its popularity.

The 6-cylinder in-line would appear to be a good lay-out for the more expensive type of engine.

I am not in favour of upside down in-line engines for the light plane; they are more vulnerable than the radial on a crash, and the induction system is difficult.

We seem to be some way off the £100 engine, but I believe the 5-cylinder radial could be made a most excellent and cheap production job.

In spite of the obvious cooling difficulties, a supercharged 2-stroke, with direct fuel injection, would appear to be at least a promising line to explore.

The 200 to 250 h.p. Engine

In this category, where price and simplicity are still of considerable importance, the radial family would seem to be able to hold the field. The objections to the 8-cylinder horizontally opposed are obvious. The 8-cylinder Hex is excellent from a balance point of view, but probably more expensive than the single bank radial.

The 350 to 450 b.h.p. Engine and the 500 to 600 h.p. Engine

The qualities required from the last two categories are approximately the same, except that the larger engine demands a greater number of cylinders, and allowing that it will probably be installed in slower machines where gearing will be necessary, the cooling difficulties will be considerably greater.

By the courtesy of the Wright Company, and the United States Air Corps I have been permitted to show Fig. 35 of the Wright Company's latest type 12 cylinder Vee in-line air-cooled engine of 1456 cubic inches; the diagrams at the side show the interesting mounting for this engine and Fig. 36 shows two views of a similar type engine, the air-cooled Liberty, in a single-seater Scout.

The Wright Vee 1460 is a very interesting engine indeed, and represents the very latest practice in compact air-cooled in-line layout, for which so much has been claimed of late.

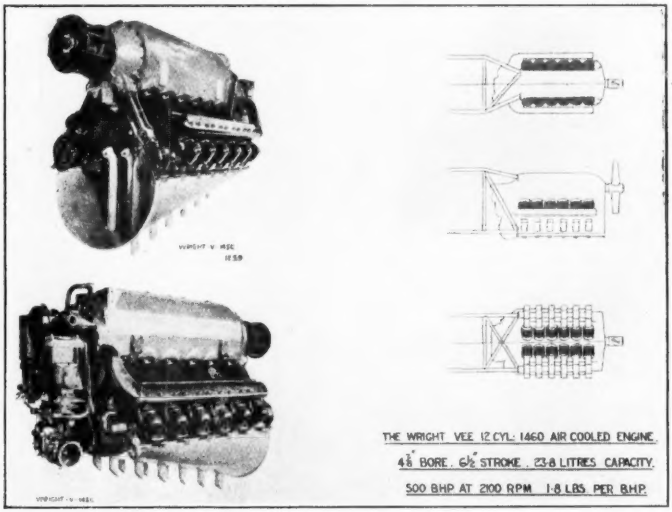


FIG. 35.

Proposed method of mounting engine.

The burning question is how much less drag, compared with the radial, will an engine of this type give when the opening in the cowling is sufficient to provide the necessary cooling air to each cylinder.

Without in any way criticising the in-line Wright engine as a design, I believe the radial will require a good deal of displacing, at any rate for the third category, provided it can be installed in a suitable manner.

Fig. 37 shows in diagram form and to scale, two similar machines, with 9-cylinder radial and 12-cylinder Vee air-cooled engines, of approximately 400 b.h.p. In the case of the radial engine machine, the drag has been reduced by a suitable lay-out and engine cowling, and the weight of the aircraft with radial engine will be undoubtedly less.

In the large engine category the radial family should all score on weight, cost and maintenance. The drag depends upon the type of machine and consequently the body behind the engine.

If the machine is such that the body allows a complete fairing to the engine

the drag will probably approach that of the in-line engines, and the cooling should certainly be an easier proposition than on the latter.

The horizontally opposed 12-cylinder looks to be a very useful engine for multi-engine machines.

In conclusion, I would like to thank all those firms, both in England and America, who have so readily come forward with information, without which this paper would have been impossible, and also Messrs. Owner and Fraser, of the Bristol Engine Department, for assistance in compilation of the Tables.

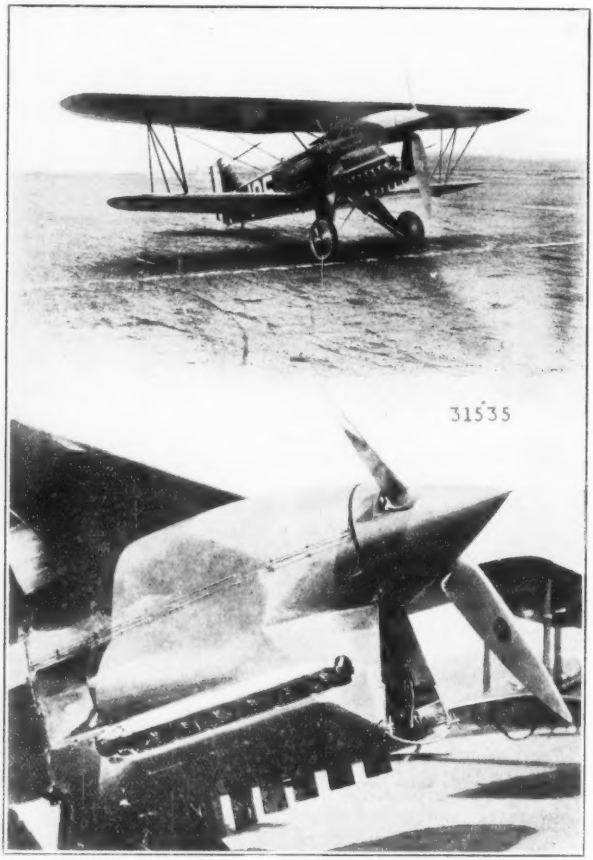


FIG. 36.
Inverted Air-Cooled Liberty 12-cylinder Vee Engine, installed in United States Air Corps single-seater Scout.

DISCUSSION

Mr. PYE: He had not come prepared to open the discussion, and he feared he was, therefore, not in a position to do justice to the paper. He had always held the belief that the really great man was the man who had no secrets, and that the thicker the veil of mystery that was drawn round any

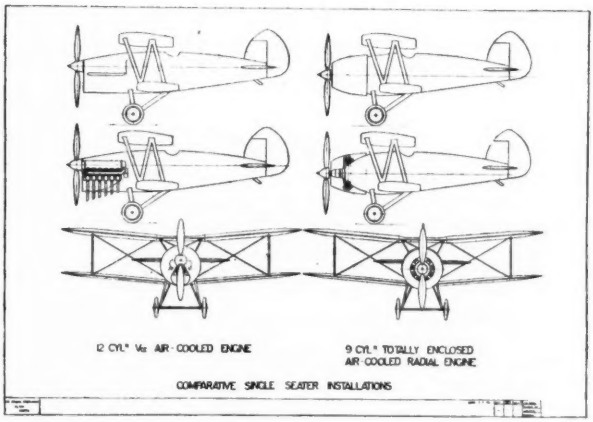


FIG. 37.
400 b.h.p. 9-cylinder Radial and 12-cylinder Vee Air-Cooled Engines. Comparative installations in single-seater machines.

particular development the more likely it was that there was nothing behind it worth concealing. The truth of that was well illustrated by Mr. Fedden, who was prepared to come and lecture to anybody with ears to hear and brains to understand and give them the full benefit of his unique experience. Another thing about Mr. Fedden was that being a big man he was not above taking advice from the little people, and again, being a big man, there never was anybody more generous in suggesting that his successes were due to the advice of the little people. Whereas in reality nobody but Mr. Fedden could have delivered the goods, because he had the eye to discriminate between suggestions which might be turned into something effective and practical and those which could not.

Mr. Fedden had made out such a good case for the reliability of the air-cooled engine in service that there was really very little to say on that point except to congratulate him. As choruses of praise, however, had a dullness only to be tolerated in heaven, he would turn his attention to two points in regard to which it seemed to him that the advocates of the water-cooled engine could, so to speak, "get it back" on the air-cooled engine designer. The two points he had in mind were fuel economy and head resistance. The growing importance of fuel economy was really the result of the skill of men like the author in reducing the weight per h.p. of the air-cooled engine. If we took 1½ lb. per h.p. as an all-round figure for an engine of that kind, such an engine would use about 55 lb. per b.h.p.-hour of petrol and would therefore consume its own weight of fuel in 2½ to 3 hours. Therefore, a saving of 10 per cent. in the fuel weight at the start was equivalent, for a flight of that length, to a saving of 10 per cent. on the engine weight. He was not at all sure that the questions of fuel economy and reduction of drag in the air-cooled engine did not both come down to the problem of more effective cooling, because were we not, in the air-cooled engine, relying upon a little extra petrol—a little more than was wanted in the cylinders for power purposes—to get rid of those tiresome hot spots which promote detonation and limit the power output? Therefore, more effective cooling in the case of the air-cooled engine might very likely bring down the fuel consumption more on to a level with that of the water-cooled engine.

Mr. Fedden's remarks on installation were particularly interesting. The

paper suggested that the cure for the large head resistance of the air-cooled engine was by means of cowling and that the cure for the variety of performance of the same air-cooled engine in different installations would also appear to be in the direction of efficient cowling. As a preliminary to this question of the design of the most efficient cowling, he would like to put the question whether sufficient attention had been paid to the effect of what might be called the intimate details of design in the cylinder head upon the effectiveness of the air stream over the cylinder head. It was often the practice simply to shove the cylinder head out into the air stream. That was an inefficient way to get the cooling done. An air stream of 100 miles per hour might give quite satisfactory cooling, and if the air stream were increased to 150 miles per hour, although the effective cooling would not be increased by 50 per cent., it was probable that the drag would be more than doubled. Another way of looking at it was to say that the air temperature coming off the cylinders was a very long way below the 280° to 300° C. of the hot spots in the cylinders. In other words, when looked at from this point of view, air cooling was an inefficient process. Therefore it was important to consider whether it was possible, by carefully studying the effects close up to and around the details of the cylinder head, to get more effective cooling with a much lower air speed than the average speed near an exposed cylinder. That was what was wanted for successful completely enclosed cowling. He remembered some experiments carried out by Ricardo some two or three years ago in which an electrically heated pea was used at the end of a long stalk. The small metal pea contained a thermo-couple, and by measuring the rate at which heat was carried away from that pea when it was placed at various points round the little obstructions of a cylinder head and even between the fins, Ricardo was able to measure the effectiveness of the air stream for cooling, at points which it would be impossible to get at in any attempt to measure the speed of the air. During these measurements of the actual rate at which the air stream was capable of carrying off thermal units, some very striking results were obtained. By moving the pea hardly more than a quarter of an inch, it was possible sometimes to obtain a sudden reduction in the amount of heat carried away by the air stream. In this way the existence of pools of stagnant air caused by obstructions was shown up. He was not suggesting any highbrow research, or groping in the dark, but a perfectly practical investigation which he conceived each engine designer might carry out on his own engine, and thus seek out the effectiveness of the air stream at all points round his own cylinder head. That was put forward as a suggested first step towards a solution of the problem of designing an efficient cowling and of the reduction of the drag. It might even be worth while—and again this was merely a suggestion—to conduct the air stream to certain critical spots round the exhaust valve, and to the most difficult parts to cool, by tubular ducts. In this way the air might be taken to the points where it was most wanted, and this might form the preliminary to a complete and carefully designed system of air passages by which it would be possible adequately to cool an engine when completely enclosed in a cowling, and so sweep away the last reproach which the water-cooled merchants could aim at the head of such gentlemen as Mr. Fedden!

Mr. HANDLEY PAGE: The author rather went beyond the aircraft engine problem and turned to the question of aircraft design when he dealt with the way in which the engines should be installed in the aeroplanes, and he could not help feeling that the author had gone wrong in doing so. The aircraft engine manufacturer very often thought that when he provided a nice sectional drawing of the engine installation with a good streamline shape from the propeller spinner to the fuselage out of which certain of the engine might project, the air would flow round it in a nice easy way and cause very little head resistance. The engine manufacturer very often did not realise—and

the authors rather fell into the same error—that the projection of the cylinder head perhaps put up the resistance of the fuselage by four times and it would be better if the head were not there. Looking at slide 38 shown by the author it appeared that he has the exhaust ring collector in front of the cylinder. The exhaust gases therefore conveyed a nice amount of heat to the air flowing over the cylinder and this unfortunately was conveyed to the top of the cylinder head which had to be cooled! The air did not flow directly backward between the cylinder and over the fuselage; it very often was deflected straight upwards and was very similar to what would be the case if instead of the cylinder heads there were a series of plates at right angles to the air deflecting the air out radially from the fuselage. In consequence, there was a tremendous increase in head resistance. Experiments had recently been conducted quite successfully in wind channels and on full scale, which showed how the resistance could be cut down by fitting rings round the outside of the cylinder and cowling in the front. That was a case of the aerodynamic side of aviation having tackled the problem for the aircraft engine manufacturer, and it had not been the case of the aircraft engine constructor tackling it. The research people on the aerodynamical side had tackled this problem and had shown how it could be done, and he could not help feeling that if more attention was paid by the aircraft engine constructor to that side, and if he took more lessons from the Aeronautical Research Committee and particularly from the aerodynamical side a great deal of the head resistance, which was the bugbear of the air-cooled engine, could be reduced. Whether the air-cooled engine be of the radial type or the in-line type he rather felt that eventually when they were properly cowled in, the head resistance would be very much the same in the two cases, but there was one inherent disadvantage of the air-cooled engine as compared with the water-cooled engine, and that was the question of the pilot's observation capacity or visibility. Looking out from the pilot's cockpit in the case of a water-cooled engine there was a good view, but in the case of the air-cooled engine of either variety mentioned in the paper there were enormous frontal areas which obscured the pilot's view, and the aircraft engine manufacturer must not only pay attention to cooling but also to reducing this frontal area in order to give the pilot more visibility.

There was one other point to which attention must be given in connection with the exhausting of the gases from the engine. In a recent type of cowling being developed in America, the engine was completely cowled in and the air flowing through was led away parallel to the fuselage and therefore had a minimum of head resistance. No adequate means, however, were provided in that design for dealing with the exhaust gases as far as he could see. They were ejected out from short pipes into the air stream which flowed backward in between the fuselage and the cowling, and presumably a good deal would reach the pilot. On that score there was a good deal more hope for the ring type of cowling that had been developed at the R.A.E. in which the ring went completely round the outside of the radial engine. That, unfortunately, suffered from the fault of increasing the size of the engine installation and consequently increased the difficulty of the pilot's visibility.

It was always a pleasure to listen to a paper by Mr. Fedden. The attention now being given to air-cooled engines in all countries was such that one was apt to forget the pioneer work for which Mr. Fedden had been responsible. He well remembered the early days towards the end of the war when air-cooled engines of the stationary type were starting to find favour and how the author pushed them forward. It was from that pioneer work that development had taken place in most countries of the world, and it was for that reason he wished to congratulate Mr. Fedden not only on this paper but also on the pioneer work which had preceded it and of which he had given so many details in the paper.

Major KUHNE (War Office): Concerned as he was with the development of mechanical vehicles for military purposes, he was beginning to wonder whether the time had arrived to begin some experiments with air-cooled engines for the more commercial types of military vehicles. The present weather rather brought it home to one that the same water-cooled engines were expected to operate efficiently in extreme cold, in the milder temperatures on the Continent, in the hot climate of the Sudan, or at the high altitudes of the North-West frontier of India. This gave some idea of the problem to be faced with water-cooled engines which had practically a constant rate of water circulation and no variable gears to the fan for the air supply. The critical water temperature of 212°F. gave really a very small, indeed often *no margin* of safety. A period of 400 hours between overhauls was mentioned in the paper for air-cooled engines in the air. The cost of new material at these overhauls appeared not to be high. If this were applied to a commercial vehicle running at an average of 20 miles an hour, we arrived at a total of something like 8,000 miles. It was possible to carry relatively more weight on a motor vehicle than on an aeroplane, and so the vehicle engine might be made perhaps a little less efficient in respect of lbs./h.p., and therefore giving better wearing qualities. The great problem, of course, was to get a flow of air which would keep the engine cool enough, and it was not known what percentage of the h.p. would have to be absorbed by fans or blowers. Vehicles such as the Army was using now, though fast on the road, often had to travel for considerable periods at a very slow speed on rough ground across country. The engines might be exerting something like full power, at a very small or even a negative vehicle speed through the air.

It was interesting to learn that "in-line" air-cooled engines were becoming more popular for aero work, as this type was more suitable than the radial type for automobile work.

A rough summary of the merits and demerits of the air-cooled engine from the military vehicle aspect, and relatively to the water-cooled engine, appear to be:—

(*a*) Higher power weight ratio;
(*b*) Less susceptible to variation in climatic conditions—no "freezing up"—no loss of water in hot countries where water may be vitally precious—early establishment of normal running temperature after starting cold;
(*c*) Less vulnerable under enemy action (no radiator, etc.);
(*d*) Probably more susceptible to low grades or to variation in quality of fuel and lubricant—may need benzole mixture or other anti-knock or doped fuel;
(*e*) More noisy;
(*f*) More frequent overhaul, but possibly easier to overhaul;
(*g*) Greater heat effect on driver in hot climates, especially where the driver is located alongside or over the engine;
(*h*) Probably requires a large air blower, which may absorb considerable power but is possibly no more complicated to maintain than a water-cooling system.

It was difficult to foresee what might happen. A change over to air-cooling to secure the substantial advantages offered might be followed by reversion to water-cooled compression-ignition engines for other reasons.

He hoped that, under the stimulus of so interesting a paper, some designers of commercial vehicles might be moved to consider the development of air-cooled engines and to give their views as to the trend of future progress.

Captain WALKER: Referring to the question of maintenance and the figures quoted in the paper in connection with the Cirrus engines used at the Bristol and Wessex Aeroplane Club, he thought the cost of maintenance of these engines in service, excluding insurance and depreciation but including fuel and

oil based on a cruising speed of 80 miles an hour was less than 1¼d. per mile. This compared very favourably with motor cars. He agreed with the author that the question of air cleaners and internal air intakes is of the greatest importance particularly in view of the state of the average aerodrome in the summer months, when the dust resulted in great wear to the cylinders of small engines such as the Cirrus. As to the frontal area of the in-line engine as opposed to the radial engine, he believed the author's remarks were based on the V engine, but it seemed to him that the area of the in-line engine would be reduced if it were a single bank of 6 or 8 or even 4 cylinders. As regards the inverted in-line engine, what did the author mean by carburation troubles in connection with this? As Mr. Pye had said, it was quite essential to conduct the air flow to each specific cylinder of an in-line engine, and if that were done satisfactorily he did not think the question of cooling would be so insurmountable as it might at first appear. The pilot's view had been raised by Mr. Handley Page, and the inverted engine would overcome this difficulty.

Mr. BRIAN (Australia): There were air-cooled engines running in Australia, where the idea of air-cooling had been seriously taken up. He could only speak from experience of the Cirrus and the Jupiter engines, but troubles with water-cooled engines in Australia had been very serious. It was necessary to make radiators that were three times the size of the normal radiator, but experience with the Jupiter engine had been that there were no over-heating troubles. That was with the direct drive Jupiter, and the point came out that the air-cooled engine operated at a higher temperature than the water-cooled engine, and therefore there was not such a big relative varition from the temperature of the atmosphere when operating with an air-cooled engine, as there was with the water-cooled engine. The question of conducting the air definitely to various parts of an in-line engine had been tackled in Australia, and the result of juggling with cowls and altering the air stream on the Cirrus engine had given better running results and less tendency to pinking in the very hot weather. From the point of view of hot climates the air-cooled engines had a very definite advantage, and was not up against the same problems as the water-cooled engine on account of the higher temperature which resulted in less effect from variation in the climate.

Colonel HUTCHINSON: He could not speak of the aero engine, but as had already been suggested there were uses for the air-cooled engine on the ground. The air-cooled engine for motor vehicles was by no means new, as Dr. Lanchester many years ago made a well known 10 h.p. air-cooled engine and a very excellent car it was. That was some 25 years ago, and since then there had appeared one or two well known air-cooled motor car engines, particularly the Franklin and more latterly the Sara. He had once had a very interesting ride for a distance of over 200 km. in France on a Sara car, and was astonished to find how excellently it kept cool under conditions of very hard driving. He was interested in the development and application of the air-cooled engine to tropical conditions, because it requires no water, and in a country where water was very scarce and every pint of water was wanted the possible use of air-cooled engines assumed an importance which it was difficult to realise in this country. Engines required to work in tropical heat were also required to go up to high altitudes where the temperature was down to freezing, and the difficulties of over-cooling with water-cooled engines and of frozen radiators might be serious. On the north-west frontier of India, engines could be run from the depth of winter to tropical conditions and back again the same day. Thus the range of temperature was very much more serious than in this country. It would be very interesting to have some comparative figures of the nature suggested by the Chairman, and it seemed to him that it would be a fairer comparison to compare the working hours of the air-cooled aero engine with the water-cooled aero engine. He thought on

the ground some important results were likely to follow tests with oil and air filters. He was interested in the remarks made on dust encountered up in the air; he had rather thought we had most of it on the ground, but apparently there was a good deal in the air also.

Mr. FOORD: The paper rather behoved one to consider what constitutes good service. Aero engines, whether air-cooled or water-cooled, were expected to be reliable, to be able to fly under extremes of climatic conditions, hot or cold, to be run at low cost and maintenance, to be efficient and not to be fastidious in their demand for high-grade fuels and oils. The air-cooled engine was at least the equal of the water-cooled engine in these respects, but personally he rather thought that some of the aero engine designers had been living in something of a fool's paradise for a few years with regard to the demand for high-grade fuels and oil. Therefore it was interesting to see from the paper that steps were being taken to obviate this, particularly with regard to lubricating oil. British aero engine designers had always used very expensive castor oil for lubrication, whereas the Americans had concentrated on mineral oils with very good results. That policy would have to be followed in this country on all types of aero engines and use made of as low grade a fuel as possible, a fuel which could be obtained locally wherever one happened to be. One should not have to give aero engines copious drafts of benzol in order to ensure reliability of operation, and it appeared that the metallic dopes would help in that direction.

Mr. MUNTZ: He would like to deal further with the point as to fuel raised by the last speaker from the point of view of the private owner of an aeroplane who had to use engines of anything from 100 to 250 h.p. Whilst experience showed that a good fuel gave the best results on the commercial type of machine, there was going to be a vast market for the small private owner who was not in the position always to use the best types of fuel and oil. Human nature being what it was, the average person of this type would occasionally use any old fuel, and the engine manufacturers would have to design from that point of view. The engines must not be designed solely to work with heavy benzol mixtures or ethyl. It would be necessary for the private owner to be able to put in any spirit safely. This led him to the question of warming up. He was engaged in an enterprise which would have to operate and look after aircraft in the future. A great amount of time was wasted in warming up aircraft engines, and the general experience was that the small air-cooled engine required a great deal more warming up than the water-cooled engine, because with the water-cooled engine the shutter of the radiator could be put down and thorough warming be quickly achieved. No doubt the aircraft or engine manufacturers would supply some form of cowling to stop the draught going on to the cylinder during warming up, and this was quite an important point to the private owner or small commercial user, because so many of them wanted to start up the engine and be in the air inside a couple of minutes. Here he would like to emphasise that detonation was usually only destructive when it occurred before the engine was thoroughly and uniformly heated. When cold, the clearances between aluminium and cast iron cylinder walls are very large indeed, and this, combined with the probability of local heating resulting in distortion, make it essential to get the engine thoroughly warmed before asking it to develop full power. If the engine is anywhere near detonating on a good petrol, then with a poorer quality petrol detonation will set in just when it is likely to cause real damage. Therefore, he would like to make a plea that it should be possible to warm up small air-cooled engines more rapidly than at present, and also that they should continue to be able to use any normal fuel so that the machine could safely be taken anywhere. With regard to the question of four-cylinder versus the six-cylinder in-line type of engine, one point was the ease of starting up, which had not been mentioned. Here he was speaking of 100 h.p. engines. The

four-cylinder engine could be more or less easily started up by a strong man swinging the propeller, but there were a number of people learning to fly at the moment who had not the physical strength or were not tall enough to reach the propeller. With the six-cylinder engine compression pressures would be less and probably one swing would be sufficient to get over two compressions. Finally, it would be interesting if the author would make a few remarks on the question of the radial type of engine when used as a pusher. Arising out of Mr. Pye's remarks, it seemed to him that the air flow must obviously be at a lower velocity past the cylinder, and, provided there was adequate cooling, the radial engine in this position would have a real superiority over the other types of engines.

Mr. LANKESTER PARKER: During his flight round England last autumn, using a Cirrus engine, he only used three pints of oil in a 14 hours flight, and as the average speed was 78 miles an hour, this oil consumption compared well with that of any car. With regard to the radial engine obstructing the pilot's view, most of the speakers had been referring to the single engine machine, but with the three engine type the question mentioned by Mr. Handley Page did not arise.

Mr. PLATT: He spoke as a humble automobile engineer in an assemblage of aero engine experts, but he would like to know whether Mr. Fedden thought the fact that many people must be noticing that air-cooled engines were used on air liners would tend to overcome the prejudice which undoubtedly existed against that type of engine for the propulsion of motor cars. Speaking as one who had made a number of journeys in passenger aircraft, he thought that the air-cooled engine was noisier than the water-cooled type and that this was a disadvantage from the point of view of comfort. Major Kuhne had compared the performance of an aero engine with that of a commercial vehicle engine in a way which he thought was unfair to the former because the distance covered should be taken as the criterion of reliability in any transport vehicle and not merely the time of running. Thus, in a period of 400 hours between overhauls, such as was mentioned in the paper, an aeroplane would probably have covered 40,000 miles under conditions approaching to full throttle, whereas in the same time a commercial vehicle might only cover 8,000 miles. It was certainly an achievement for the engine of any means of transport to cover 40,000 miles without attention and one which must make automobile engineers realise that they had something to learn from the aero engine.

Colonel FELL (*contributed*): He had read Mr. Fedden's paper with great interest, and having been associated with Mr. Fedden for so long while at the Air Ministry, he found himself well able to appreciate Mr. Fedden's point of view regarding the service which air-cooled radial engines were giving.

He would, however, like to question certain statements in the Introduction, which did not seem to be in accordance with history. Mr. Fedden has stated that "as lately as four years ago the practical advantages of the air-cooled engine were only tentatively appreciated by the aircraft constructor." The first aircraft engine which Colonel Fell had ever seen was an air-cooled radial; this was many years before the War and was in use in a flying school held on the sands at an East Coast seaside resort.

In the early days of the War, air-cooled engines were practically exclusively used by the R.F.C., both of the air-cooled radial and in-line types. An engine which held second place for reliability throughout the War was an air-cooled engine, namely, the R.A.F. 4A—a 12-cylinder V-type of engine, though for all high performance aircraft the air-cooled rotary radial was found to give the highest performance.

Towards the end of the War the water-cooled V-type engine of both British and Continental designs, owing to the advance of knowledge of construction, superseded the air-cooled for most classes of work. These engines were, after the War, again superseded by the highly developed air-cooled radial. Perhaps

in the near future it might be found that further developments which have taken place in water-cooled engine design may cause this type again to oust the air-cooled radial from the position it now holds. It seemed that whether the air-cooled or the water-cooled type was supreme had in the past depended upon which type had, as the result of technical development, been advanced to the highest position as an engineering job.

He found himself particularly in agreement with Mr. Fedden's remarks relating to air-cooled in-line engines. During his time at the Ministry he had frequently examined this problem and it had seemed to him that however an air-cooled cylinder was placed it must offer the same drag, as it was, of course, essential that air had to be passed over it at high speed. Placing the cylinders in rows instead of as a radial for various reasons specified in Mr. Fedden's paper, resulted in a very much heavier engine in the case of the former. If one examined the history of air-cooled in-line engines and radials (whether of the rotary or static type did not really matter), it would be found that the weight of the in-line engine was always in the region of 60 per cent. greater than for the radial for a given horse-power, though there was no doubt that the cylinder construction used in the two types represented about the same standard of development. The following table illustrated this:—

		Rated H.P.	Type.	Weight in lbs.	Weight/B.H.P. normal.	M.E.P.
1914	(*a*)	80	Renault 8-cyl. V	480	4·7	82
	(*b*)	80	Gnome 7-cyl. Rotary Radial ...	212	2.82	75
1915	(*c*)	90	R.A.F. 1A. 8-cyl. V	450	4·5	89
	(*d*)	100	Mono 9-cyl. Rotary Radial ...	294	2.35	101
1916	(*e*)	140	R.A.F. 4A, 12-cyl. V	680	4·5	89
	(*f*)	150	B.R.1. 9-cyl. Rotary	408	2.3	105
1917	(*g*)	180	R.A.F. 4D. 12-cyl. V	660	3.6	100
	(*h*)	200	B.R.2 9-cyl. Rotary Radial ...	500	2.1	106

Reply to Discussion

Mr. Fedden: Speaking first with regard to Mr. Pye's remarks concerning fuel consumption, if we were honest we must admit that, based on the Ricardo tests, an air-cooled engine would have a compression of about 0.4 of a compression ratio lower than the corresponding water-cooled engine of comparable design.

That being so, we would at once deduce the fact that, other circumstances being equal, the fuel consumption must be worse. We know, however, that under working conditions other circumstances are not necessarily equal, and what was wanted was that the water-cooled people should come out into the open and say what their fuel consumption was.

Personally, he did not know of any comparable figures, although he rather suspected that the figures obtained from the water-cooled engine on the bench, with ideal temperature control, might not be so good under ordinary working conditions, and there might not be such a big difference between the two engines in this respect when they were actually operating in the air.

Fortunately for the air-cooled man aeroplanes were not primarily fuel carriers, and did not stop in the air such a very long time. It did not pay, either from the technical or commercial point of view, to operate them for long non-stop flights, and for this reason he felt that the air-cooled engine in the matter of fuel consumption might not be seriously different from the water-cooled engine, although he did not know the actual comparative figures.

Incidentally, the weight saving with the air-cooled engine was considerably greater than the 10 per cent. postulated by Mr. Pye.

When aeroplanes were required to stay in the air for long periods, the answer would be the compression ignition engine, and he believed the air-cooled com-

pression ignition engine would be able to fill the bill, and the discrepancy—if in practice there was a discrepancy—would not be as great between the air-cooled compression ignition engine as it is between the petrol air-cooled engine and the water-cooled engine. He quite agreed with Mr. Pye's point with regard to the intimate details of the cylinder head, in spite of what Mr. Handley Page had said about the engine people, although far be it from him to enter into a discussion on aerodynamics, or say anything counter to Mr. Handley Page, whose views were generally absolutely right.

The trouble was that an air-cooled engine was put into one aircraft and the hot spot was taken on one cylinder, and then the same engine was put into another aircraft, but the hot spot was somewhere else. That was a very difficult problem, and that was why he submitted they should try to serve up air-cooled engines in such a form, either by complete cowling, or in such a way that the cooling would not vary owing to different conditions in different machines even at the same speed in the manner that it did at present. If, therefore, it was possible so to arrange the lines of the head that the engine could be completely cowled in, then he believed there would be a great opening for modifying the design of the head, and the same cooling result would be secured on every engine installation.

With regard to Mr. Handley Page's remarks about the exhaust ring, he believed it was possible to incorporate the exhaust ring with a complete cowling. Mr. Handley Page had mentioned about the exhaust ring being led away in the form of flattened pipes, and that was shown in the American N.A.C.A. report, where one could see black blotches of exhaust smoke all the way round the fuselage.

He was entirely in agreement with Major Kuhne with regard to engines for lorries, and had been trying to persuade a friend of his, who had been in charge of commercial vehicles for some years, to design such an engine, and he could assure the motor lorry people that the saving in warming up and in wear and tear, as well as in diluting the fuel, would be very important.

In reply to Mr. Walker, he did not deal with the 8-cylinder in-line engines, because he was limited as to the size, except in the second category he had mentioned, because the crankshaft size became so long and torsional troubles became serious.

The Germans tried to make a 320 h.p. Mercedes of this type and this was a serious problem. What he meant by carburation difficulties with the upside down engine was that if there was to be a decent flow in the induction pipe, the carburettor had to be somewhere down on the under-carriage.

With regard to Colonel Hutchinson's remarks and the Sara engine, he had tried one of these about three years ago and ordered one, but it did not come. It was something like a car he had had to do with previously. He had heard that the Sara car was to be built in England, and he hoped it would, because he would like to see an air-cooled engined car in this country.

He had no comparative figures with regard to overhauls of water-cooled versus air-cooled engines, as asked for by Colonel Hutchinson; indeed, it was these sort of figures that were badly wanted, and a great deal of good would be done if we could get them.

Dust in the air was a very real trouble. Recently he had had photographs sent him from the Eastern route of a Jupiter engined machine that had passed through a sandstorm 10,000 ft. up, and the machine looked as if buckets of flour had been poured over the rocker gear. The dust had to be scraped off the head of the engine, and it was so fine that it was a really tough problem to trap it with any form of centrifugal cleaner.

He quite agreed with Mr. Muntz's remarks as to being able to use any old fuel. At the present time it was possible to use any old fuel on any old car, but the trouble was that aeroplane engines, with their higher compression ratios, did not at present like any old fuel, and even some cars which used similar

compression ratios did not. At the same time, he believed the Cirrus would practically use any reasonable fuel.

In referring to warming up, Mr. Muntz had taken one of the great points in the paper. At first he had thought air-cooled engines were not good for warming up, but now it was one of the matters upon which he and those working with him were congratulating themselves upon.

Two years ago there was a competition in Sweden, when two British firms, the Armstrong-Siddeley and his own company, competed with air-cooled engines against three water-cooled German engines. The machines were kept in the open at 30 deg. below zero, and when the respective mechanics were let loose to get the machines into the air, the two British machines were in the air within 2½ minutes, whereas the first of the German water-cooled engined machines did not get into the air for an hour and five minutes. In view of this, he rather felt that Mr. Muntz must be confusing the ordinary in-line engine, perhaps the Cirrus or the Gipsy, which were probably over-cooled, and he could not see how they could be cowled in the manner suggested by Mr. Handley Page. It might be possible to fit a louvred form of bonnet, by which the engine could be warmed up quickly. The cooling capacity of a 4-inch bore air-cooled engine was very different from the cooling capacity of a 5½ bore air-cooled engine.

He quite agreed with what had been said of the difficulty of starting up a 4-cylinder in-line engine, as compared with a 6-cylinder engine of the same type, and in the paper he had suggested that the 6-cylinder engine was a high class expensive engine and, as in the case of motor cars, it must cost more.

He did not know much about the radial type of engine as a pusher; indeed, he would like to know something more.

The Air Ministry were trying three installations, using the Armstrong-Siddeley and the Bristol engines, and perhaps we should hear something more about them later on.

His own view, for what it was worth, was that pusher machines could be cooled, but it was no good taking a tractor and converting it into a pusher. If there was a demand for the air-cooled pusher radial, special cylinder arrangements would have to be made.

As regards oil consumption, mentioned by Mr. Parker, he believed that the oil consumption on small machines is relatively lower generally than on large machines. The oil consumption of the air-cooled engine was, perhaps, not quite so good as it might be, but it is now a great deal better than it was three years ago.

He did not know much more about the layman preferring an air-cooled engine than did Mr. Platt himself, who had asked the question. Perhaps that was because he did not personally have much to do with the operation of aircraft. As an interested party, however, he would welcome an air-cooled car in this country.

If a British air-cooled engine was made he believed it would have a good sale.

As regards the noise from air-cooled and water-cooled engines, they were both confoundedly noisy, but they could be silenced down. All makers used fairly tall cam lifts and big piston clearances, and whether it was an air-cooled Jupiter engine, using a Farman reduction gear, or a water-cooled Hispano engine, using a Farman reduction gear, the engines were noisy, and that was a matter in which there must be some development. Having done some experimental work upon air-cooled cars, he suggested that the only hope in this direction was the sleeve valve engine, and he believed that an air-cooled sleeve valve engine was an absolutely possible proposition.

On the motion of the CHAIRMAN, a hearty vote of thanks was accorded Mr. Fedden at the conclusion of the discussion.

SOME LABORATORY METHODS OF AERODYNAMIC INVESTIGATIONS

Lecture before the Students' Section, January 25th, 1929.

BY T. TANNER (STUDENT).

The science of aerodynamics consists in the study of the phenomenon following upon the motion of a body through air, the object being to investigate the nature of the forces brought into action and to discover the reasons for these forces. We know from experience, for instance, that under certain conditions an aeroplane wing fails to exert sufficient lifting force to keep the aircraft in steady flight. From experiment it has been found that these conditions correspond to a breakdown in the flow of air over the upper surface of the wing, and if we can discover some means of preventing this change we have, at least, served some useful purpose.

Now air has mass and viscosity, and is capable of being compressed, so it will readily be understood that all these properties will play a more or less important part in our investigations. The mass will appear in the kinetic energy imparted by the moving body to the surrounding fluid and the viscosity as we go from one part of the fluid which is moving with a certain velocity, to another part which is moving with a different velocity.

In the mathematical treatment of the subject viscosity introduces such great difficulties that only in a few simple cases have they been overcome. For a first approximation this property is often neglected entirely, but in practice it is one of the main features which determine the type of "flow" around the body.

The effects of compressibility are negligible at all ordinary speeds and need only be considered when the body is moving at a velocity comparable with the velocity of sound through the fluid (air), such as in the case of projectiles. The tips of airscrew blades offer another example, but this problem is dealt with in a separate manner. At the speeds attained recently by racing aircraft, the effects of compressibility just begin to make themselves apparent.

The method of investigation which is apparent at first sight is to observe what actually occurs in practice and this is possible in a few cases such as the determination of acceleration forces during manœuvres, the pressure distribution over parts of the machine, performance testing, etc. In all cases it is necessary to ensure that the aeroplane is moving in still air; hence the reason for making observation flights in the early morning. Then again, the conditions of flight are by means at the command of the observer, and lastly, the installation of the necessary apparatus and the actual recording of observations, to say nothing of the personal element, introduce difficulties which in many cases are insurmountable. It therefore becomes necessary to produce the conditions of free flight as faithfully as possible, and we can do this, to some extent, in a number of ways.

First, let us consider one of the earliest methods of investigation, the whirling arm. This consists essentially of a horizontal arm constructed of streamlined tubing and wires, so that it may disturb the surrounding air as little as possible. It is made to revolve steadily about a vertical axis, the model being carried at the extreme end of the arm. The method is very suitable for cali-

brating instruments such as anemometers at slow speeds and for certain observations in relation to "circling" of both aeroplanes and airships, but difficulties are introduced with high speeds and there is always the trouble of "swirl" due to the previous passage of the model past the same point.

In the design of a whirling arm it becomes necessary to introduce a large reduction gear, usually in the form of a worm and pinion, and it must be remembered that such a gear is not reversible so that a "free-wheel" arrangement must be fitted to the arm itself in order to prevent the pinion over-riding the worm when the driving mechanism is stopped.

Another method, in common use, which does not exactly reproduce the conditions of flight but is directly related to them, is the wind tunnel, in which the model is fixed and the air is made to flow past it. Various forms and sizes of these tunnels are in use in different countries, but the objective is the same throughout, that is, to maintain a steady flow of air over a considerable cross-section. The type favoured in this country is known as the N.P.L. type. An airscrew creates a suction inside the tunnel so that we get a steady stream from the mouth downwards, which does not vary in velocity over the cross-section by more than about ± 1 per cent. except close to the walls and in the corners. The static pressure varies along the length of the tunnel and necessitates for long models, such as airships, a correction known as "horizontal buoyancy," but by designing the tunnel with a slight taper it is possible to obtain a constant static pressure along the working section.

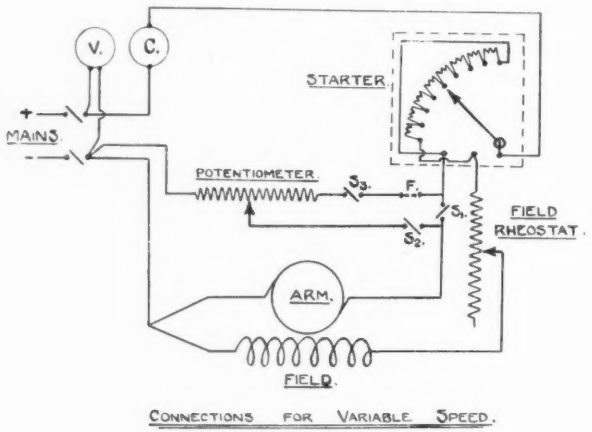


FIG. 1.

The sizes of cross-sections of these tunnels vary from 1 ft. square to 14 ft. by 7 ft., and actual wind speeds may reach as high as 150 ft. per second. The airscrew is usually driven by an electro motor with a "shunt" field, the speed being varied by means of rheostats in the field circuit. For a tunnel with a cross-section 4 ft. square, a motor of about 20 h.p. would be required and this would give speeds up to about 80 ft. per second, with a speed of about 20 ft./sec. corresponding to maximum "field" current (speed varies inversely as "field" current). Difficulty is sometimes experienced in reducing the speed below this limit of "field" control, but a satisfactory, although perhaps uneconomical, method is to connect a potential divider across the voltage mains and tap-off

from this a variable voltage across the armature, the field being maintained at maximum strength. Fig. 1 shows the electrical connections. In this way it has been found possible to run a 20 h.p. motor having a normal speed of 200 r.p.m. at a steady speed of about 6 r.p.m. The introduction of resistance in series with the armature will also effectively reduce the speed, but the current is reduced at the same time so that eventually the motor is not able to produce the necessary torque to overcome the friction of the bearings.

Another method of reducing the wind speed, but which is only adaptable to the smaller tunnels, is by means of what might be termed a baffle. It consists of a frame of wire gauze on perforated sheet metal and is fitted over the mouth of the tunnel, or alternatively, just in front of the airscrew. The effect is simply to prevent the delivery of air to the airscrew.

The airscrew and motor are usually enclosed within a distributor, which consists of a housing built up of wood slats of varying widths spaced at varying distances apart. The effect of such a diffuser is to break up the air stream as it emerges from the tunnel and to deliver it to the room again at a more or less uniform velocity. Sometimes the room in which the tunnel is built is divided into two at about the middle of its length by a cellular wall, in which case a distributor is not necessary.

Wind speeds are ordinarily measured by means of a pitot tube used in conjunction with some form of U-tube, the design of the latter depending upon the actual " head " to be measured. Thus, a velocity of 60 ft. per sec. will give a head of water of 1.46 inches. The form of U-tube most convenient for measuring wind speeds between 20 ft./sec. and 70 ft./sec. is a Chattock tilting gauge. As this piece of apparatus is a more or less standard instrument I will not attempt to describe it in detail, but will point out one or two matters connected with it. The sensitivity depends upon the ratio between the diameters of the central tube, on which the bubble is formed, and of the outer reservoirs, and the accuracy upon the screw thread and the assumption that the horizontal distance between the centroids of the surfaces in the reservoirs remains constant.

For high wind speeds it is perhaps more convenient to use a simple U-tube, one side of which has a vertical rise and fall movement operated by means of an accurately constructed screw-thread, but a " Chattock " type gauge, suitably modified to give a greater range, may be used equally as well.

The measurement of wind speeds below 15 ft. per sec. introduces considerable difficulties as the ordinary tilting gauge is not sufficiently sensitive. It is possible to go down to perhaps 10 ft./sec. by fitting the glass part of the gauge to a sort of turntable, which can be turned about the centre of the metal base or frame. Then by turning this through an angle of 60° relative to the latter we may get a reading which is exactly twice that for the ordinary gauge. Below 10 ft. per sec., I know of no satisfactory method of measuring wind speeds. Vane anemometers are not sufficiently accurate and in any case would require calibration on a whirling arm.

Another method of measuring wind speeds, and one which, at first sight, lends itself particularly to investigations near surfaces is the use of a hot-wire anemometer. In a very convenient form it consists of a piece of platinum wire 1/1000th inch in diameter and about $\frac{1}{4}$ inch long soldered to the ends of two manganin legs, which are attached at their other ends to a piece of ebonite. Current leads are soldered to the manganin legs and sufficient current (about $\frac{1}{4}$ ampere) is put through the platinum wire to make is just glow in still air. In a stream of air the wire is cooled and its resistance drops. More current is made to pass until the initial temperature, and therefore resistance, are reached, and readings of this current serve to indicate the wind speed.

An approximate law of variation between current, to maintain constant

temperature, the wind speed is given by King, who first investigated the forced convection cooling of small cylinders. It may be expressed:—

$$i^2 = a^2 + bv^{\frac{1}{2}}$$

where i = current, v = wind speed and a and b are constants; a will be the current in still air. King experimented with considerable lengths of wire, and although the law may be true for such cases, it does not quite hold for the type of anemometer described above, probably because the temperature along the wire varies considerably (only about the middle third glows).

A most inconvenient phenomenon respecting hot wire anemometers lies in the fact that the constants in the above equation change unaccountably from day to day so that a new calibration is necessary every time the wire is used. Not only does the material of the wire itself "age," but the surface collects small particles of dust and probably the temperature and humidity both have their effect.

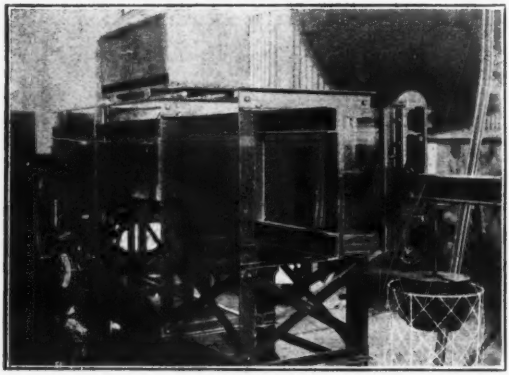


FIG. 2.

The instrument is most sensitive at low wind speeds, but calibration here becomes difficult in the absence of an absolute means of measuring small speeds. In this connection considerable use may be made of a whirling arm.

Owing to viscosity, any body moving through air is surrounded by a layer in which considerable changes in velocity occur. This is called the "boundary layer," and a complete knowledge of its nature would lead us to the determination of the skin friction forces. Attempts have been made to use a hot-wire anemometer to determine the distribution of velocity in this boundary layer. The hot wire being so small it affords a very suitable instrument for such investigations, but difficulty arises from the fact that, on approaching closer than 1/10th inch from the surface, the latter itself cools the wire, and the amount of cooling varies as the wind speed varies at some distance from the body. This surface effect seems to depend mainly upon radiation and may be said to be independent of the conductivity of the material since it was found that a piece of glass and a sheet of tinned iron gave almost the same effect. The least effect found up-to-date has been given by an unpolished wood surface. Very small pitot tubes made of hypodermic tubing have also been used for the investigation of the boundary layer.

A most important characteristic in aerodynamics, first pointed out by Osborne Reynolds, is the law of similarity. It may be stated as follows:—The motions

of viscous fluids will be similar if the size of the obstacle and its velocity are so related to the viscosity that vd/V is constant, v = velocity, d = some main dimension of the body and V = kinematic viscosity = μ/ρ. This quantity vd/V is spoken of as "Reynolds' number." Now consider an aeroplane wing with a chord of 5 feet and travelling at 90 m.p.h. The product vd in ft.-sec. units is 660, so that in order to reproduce the exact equivalent in a wind tunnel working in the same atmosphere, if we are limited to a chord of 6 inches, the speed would need to be 1,320 ft. per sec. Now we are also at liberty to change the factor V so long as the Reynolds' number remains constant, and this may be done by using a different atmosphere. Suppose we compress the air to 20 atmospheres. $V\ (=u/\rho)$ becomes 20 times smaller, so that with a chord of 6 inches again we shall only need a speed of 66 ft. per sec. in order to reproduce the conditions of full-scale. Thus we see that by the use of a compressed air tunnel, scale effect can be eliminated. Such a tunnel is in existence in America and is fully described in N.A.C.A. Annual Report for 1925.

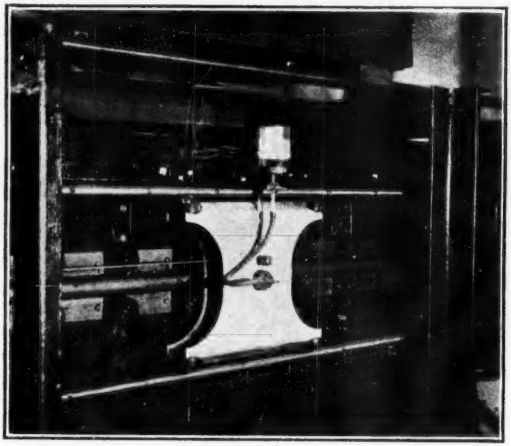


FIG. 3.

Another method of investigating fluid motion has also been developed from a consideration of Reynolds' number. The kinematic viscosity of water is approximately 1/15th of that for air at the same temperature, so that if we make a body move through water at 1 ft. per sec. we have the same conditions as the same body in the wind tunnel with an air speed of 13 ft. per sec. This comparatively slow speed enables the flow of fluid around the body to be studied at leisure. Experimental apparatus has been erected at Cambridge (see R. & M. 1065) and at the Royal College of Science. The apparatus at the R.C.S. consists mainly of a totally enclosed tank with the following inside dimensions:—12 feet long by 19 inches deep by 13 inches wide.

Figs. 2 and 3 illustrate the front and back respectively.

With the exception of the back, it is built entirely of plate glass and is filled with water to just above the top in order to ensure that there is no free surface on which waves may be generated. The back is of rather complicated design as it carries a horizontal spindle, protruding right across the tank, and a long "seal-tube." The spindle carries the model and is constrained to move

steadily from one end of the tank to the other. Innumerable small drops of oil, of the same density as water, are introduced and illuminated from above and below by mercury vapour lamps focussed into a parallel beam. The drops reflect the light through a right angle so that a camera placed in front of the tank can be made to photograph the movements of the drops as the body passes along the tank and displaces them. Then by placing such photographs underneath a travelling microscope we can find the velocity at any point in the fluid both in magnitude and direction.

Investigations by this method are limited to cases of two-dimensional flow and to qualitative experiments. No provision has so far been made for the measurement of forces, but the apparatus is as yet in its infancy and further developments may come to light with the progress of time.

No mention has been made of such piece of apparatus as that used by Hele-Shaw for demonstrating the steady flow of fluids and the free surface water tanks, but it has been shown that it is possible to use a complete range of Reynolds' number up to that which corresponds to full-scale.